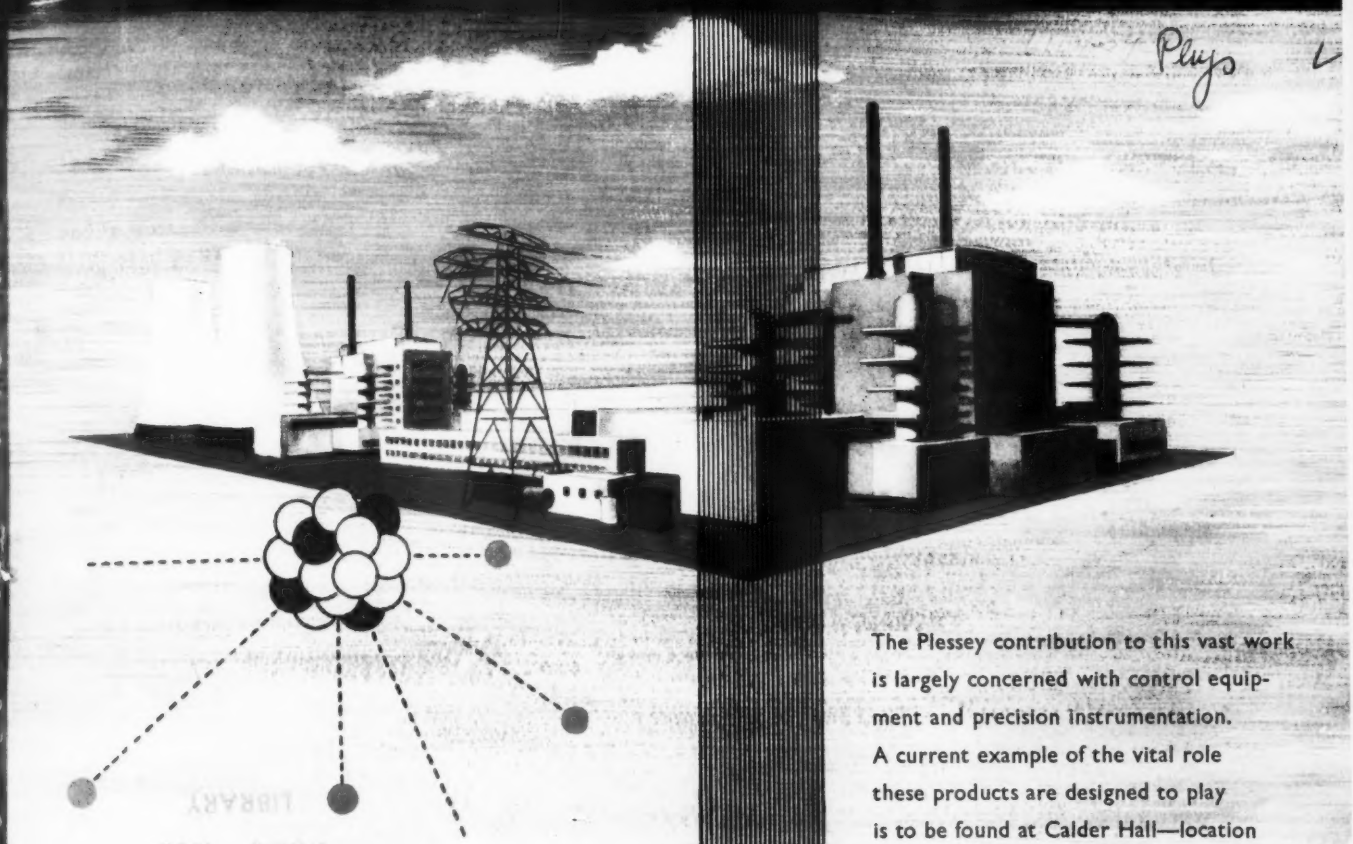
Nuclear Power

The journal of British nuclear engineering



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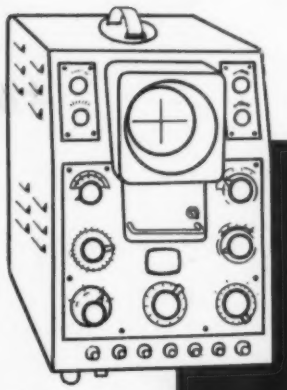

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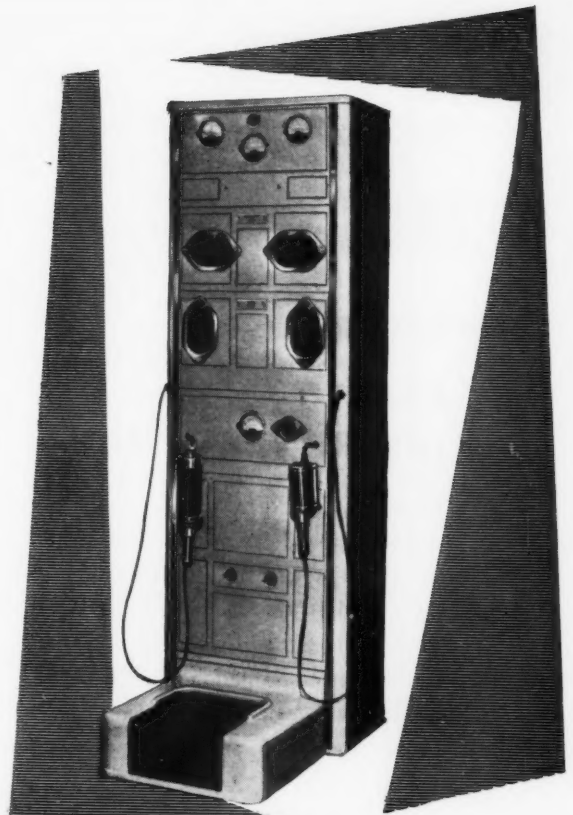

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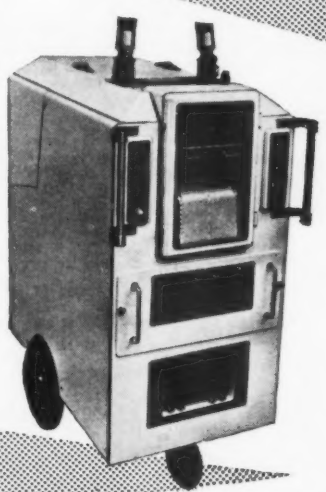

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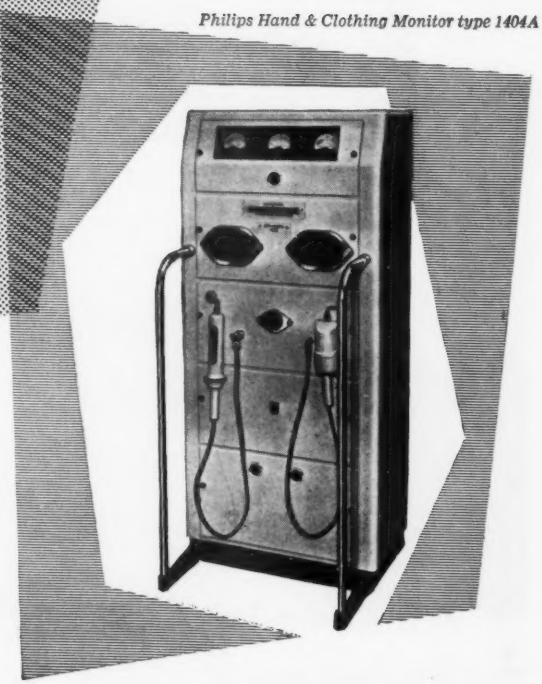

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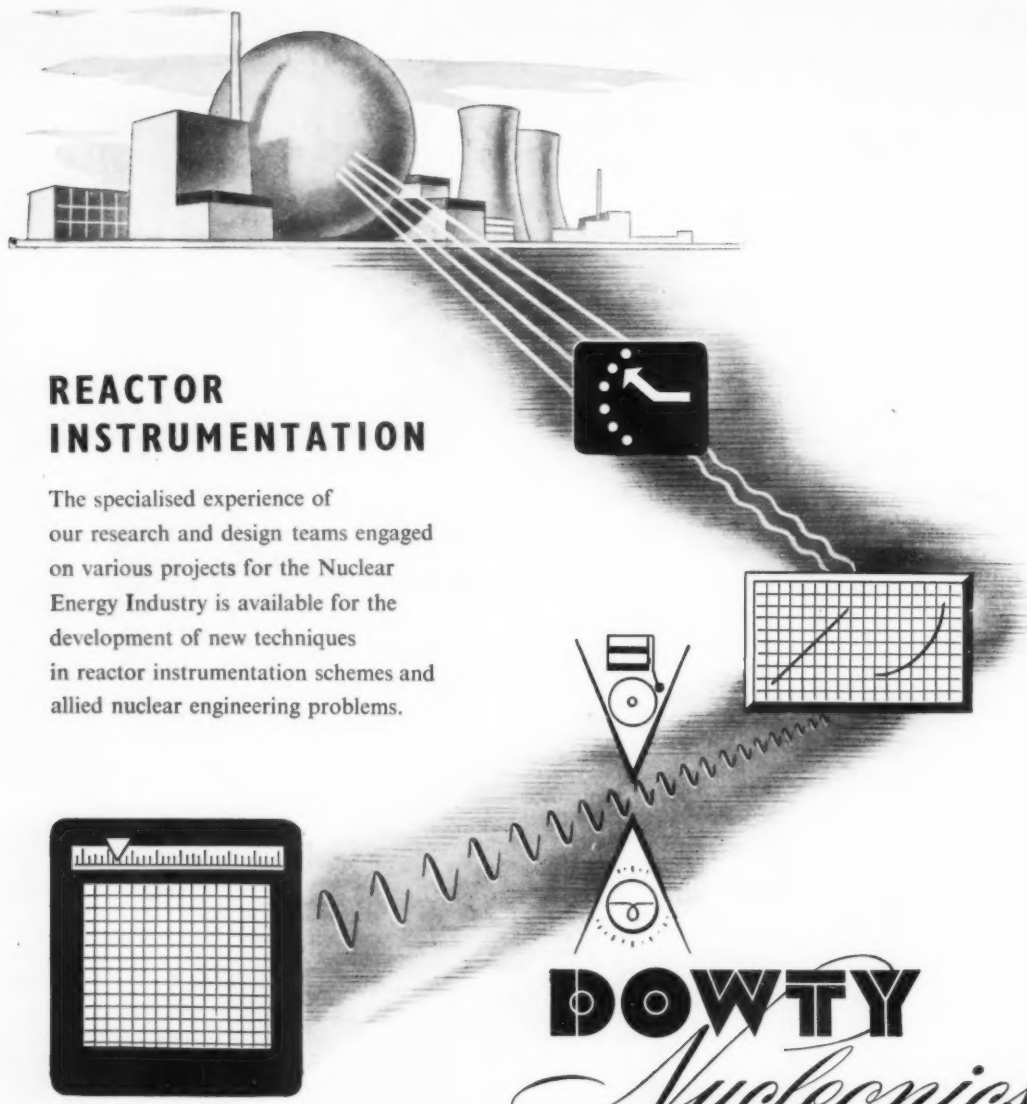

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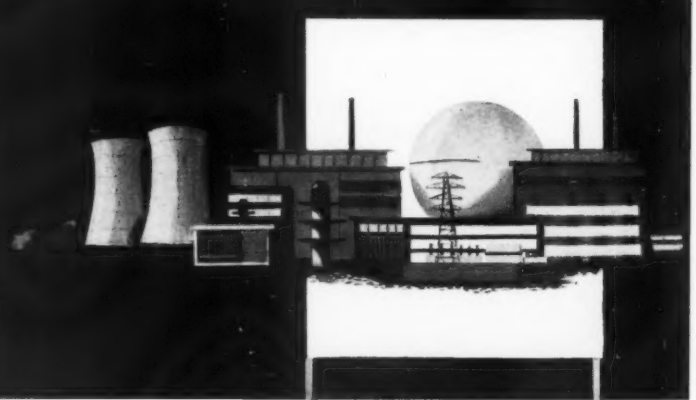

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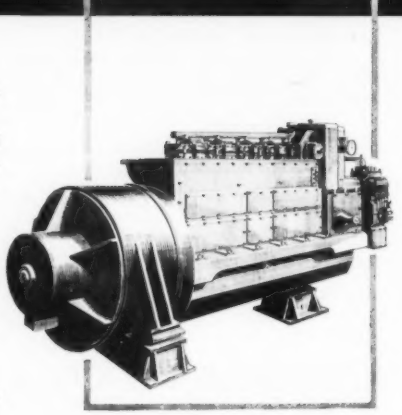

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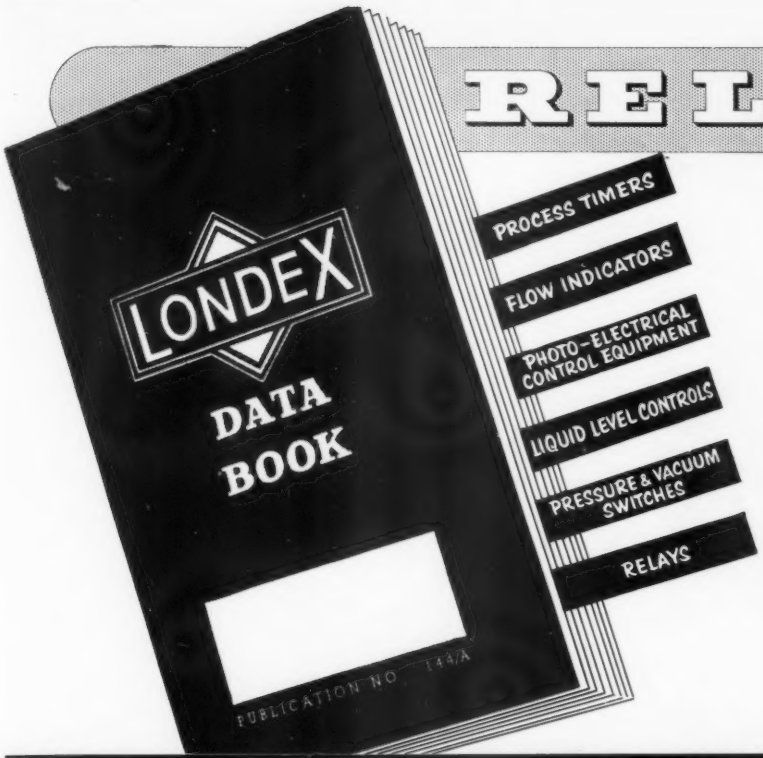

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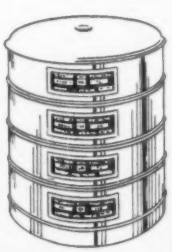

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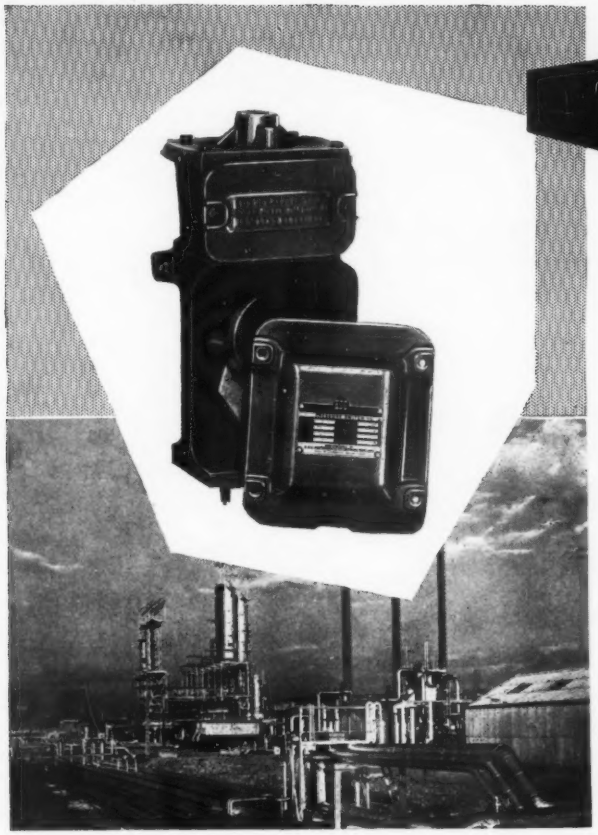

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June 1956
volume I
number II

Nuclear Power

The journal of British nuclear engineering

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Ever since Geneva, the idea of a controlled thermonuclear reaction has fascinated newspapermen who remain, as befits their trade, quite undaunted by frequent cold-water treatment from official spokesmen. Largely due to their pressure, however, it was established that Britain, America and the Soviet Union are all working on the problem with some degree of urgency. Later, in New York, Mr Strauss admitted that "Operation Sherwood" had recently received increased priority and about the same time, also in America, Sir John Cockcroft cautiously agreed that British work had reached a stage where it could be stated with certainty that thermonuclear power would be available before industry needed it. Presumably this was just a way of avoiding having to make a wild guess in public, for Britain needs at this moment any form of power she can get to relieve the intolerable pressure on her coal supplies.

Since then there have been numerous press reports from both sides of the Atlantic on "breakthroughs" —reports almost invariably followed by the customary official denial—but now we have something rather more solid to go on in the shape of Academician Kurchatov's remarkable lecture at Harwell a couple of months ago. This, in effect, was an account of what might have been a breakthrough but wasn't. There is no doubt that the Russian experiments on pulsed discharges are of the greatest importance to fundamental physics, though Dr Kurchatov made it quite clear that as far as a controlled fusion reaction for practical purposes is concerned they have led to a dead end. Which presumably is why he was able to describe them so freely.

It also implies, however, that the Russians feel very confident about their present approach to this—we quote Dr Kurchatov—"extraordinarily interesting and very difficult task". In fact, in a subsequent exchange of published letters with a British newspaperman, he offered to publish some more recent Russian work if we would reciprocate with a similar gesture. At the time of writing, however, the Soviet offer has not been accepted and neither the British nor American atomic energy authorities seem disposed even to discuss their failures, let alone give any hint of success.

All this is bound to have an unsettling effect in some quarters. Even at Geneva there were already signs of feet-dragging among some national delegations owing to a nagging doubt that in a decade or so any fission power stations they might build would be made obsolescent by the discovery of controlled fusion. This uneasiness was doubtless intensified by some remarks of Dr Bhabha who is, of course, a thermonuclear enthusiast.

It is impossible at this stage to judge whether any of these fears are well founded, but economically there is a great deal at stake. The prize is certainly great and considerable efforts are undoubtedly being concentrated on gaining it.

We have plenty of authority for asserting that the thermonuclear reaction will eventually be controlled and power thus made available, but none at all for settling a time scale. It is significant, however, that the Russians, who may be presumed to know as much about this as anyone, have just announced a programme based on fission energy extending to 1970 and that neither Britain nor America have yet seen fit to alter in any way their present plans.

Certainly, as far as we are concerned, our need for a new power source is far too pressing to contemplate any reduction whatsoever in our already inadequate White Paper programme. Nevertheless, we must be prepared at any time to face this new possibility and meet its challenge in the same way as we did when, in 1952, with one imaginative step we put ourselves in the forefront of developments with the conception of the first full-scale fission power station in the world.

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There were few mourners at the last obsequies of the London British Industries Fair, it having been recognised for some time that it had largely outlived its usefulness. We live now in a buyers' market and the halcyon days of easy selling are gone—a fact well known to industry and a challenge which it has, in the main, met. Nuclear energy has arrived too late to enjoy those now far-off days and the new industry is faced with powerful competition from the USA and the Soviet Union. Nevertheless, we are still in a relatively favourable position and it is of the utmost importance that we at least maintain it.

One way of doing this is by exhibiting at foreign trade fairs and exhibitions and the new British industry will surely welcome the President of the Board of Trade's words when he said recently that funds previously put into the BIF would now be available for assisting British firms exhibiting abroad. Nuclear power projects are essentially many-sided and it is clear that even in competition, a certain amount of cooperation is desirable.

It is good to know that the Board of Trade is to consult with the main trade organisations to see how this cooperation might be brought about and it is to be hoped that nuclear energy will not be left out.

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WORLDVIEW

united kingdom

Calder Hall critical

The first of the two reactors at Calder Hall A nuclear power station became divergent on 22nd May. The AEA announcement giving this news added: "Physics measurement and instrument checks are now taking place and the gradual commissioning of the plant will follow." It is understood that these tests will last a few weeks, after which the carbon dioxide coolant will be introduced and the power increased. Before the turbo-alternators are put on stream, steam generated will be disposed of in dump condensors.

Calder Hall A is to be officially opened by the Queen on 17th October.

Bradwell battle

Stiff local opposition to the proposed CEA nuclear power station at Bradwell on Sea, Essex, was encountered at the resumed public enquiry at Maldon on 8th May under the chairmanship of Mr H. W. Grimmitt, an inspector of the Ministry of Fuel and Power. Objections were mainly based on the grounds that a power station would ruin what Mr Tom Driberg, the former MP for the district and leader of the resistance movement, described as "the only stretch of unspoilt coast left within 50 miles of London". But there were economic objections too, and the local fishermen and oystermen fear that effluents and even warm water would harm their livelihood. Expert evidence was produced in support of these objections. Few of the witnesses had any fears of explosions or of radioactivity, and presumably even a conventional power station here would meet with resistance.

The report of the enquiry is now with the Minister of Fuel and Power, Mr Aubrey Jones, in whose hands the decision lies. Reports that there are to be two stations at Bradwell were denied by a CEA spokesman.

New "Harwell" for Dorset?

Rumours of a proposed new research station for the Atomic Energy Authority have already raised a local protest. Working on the assumption that a new establishment is to be set up near the village of West Stafford in Dorset, the Society of West Country Authors recently passed a resolution expressing regret at the proposal which, it says "would rob Wessex of the last unspoilt reminder of Thomas Hardy's Egdon Heath". A copy was sent to the Dorset County Council.

Reports about a new Harwell, to be set up somewhere near Dorchester, have been current for some time and although it is known that the Authority are seeking a suitable site in the area no, final decision has been made public. The district under consideration is fairly remote by English standards and there has been much speculation as to the purpose of the new research centre.

Kurchatov at Harwell

Soviet scientists have been working for some years to achieve a controlled thermonuclear reaction, according to academician Igor Y. Kurchatov, a member of the Bulganin-Khruschov mission, lecturing to AERE staff at Harwell on 25th April. He described laboratory experiments which consisted in passing extremely heavy pulsed currents through tubes containing various gases such as deuterium, whereby temperatures of 1 M°C were obtained in a contracted gas "plasma" detached from the walls. Neutron emissions were detected and it was assumed that the expected thermonuclear reaction was taking place. It was later found, however, that neutrons also appeared at much lower currents in a region where fusion could not be expected. Speaking later, Dr B. F. Schonland, Harwell's Deputy Director, said that the Russian experiments had been beautifully performed and showed that an entirely new and unexpected effect had been discovered. He added that Harwell had been engaged in similar work for some time, but that no results had yet been announced.

An earlier part of Dr Kurchatov's lecture dealt with some aspects of nuclear power developments in the USSR. During 1956–60, he said, five full-scale power stations would be built. Two of these will have water-moderated air-cooled thermal and epithermal 200-MW reactors with 70-MW turbines using steam of 450 lb./sq in. dry saturated. Another station would have graphite-moderated steam- and water-cooled reactors based on the 5-MW prototype station. These would produce steam at about 1300 lb/sq in. superheated to about 900°F, for supplying turbines of 200-MW total output. A third type visualised for the first stage is to be a heterogeneous heavy-water-moderated gas-cooled reactor supplying steam for turbines of 200-MW total output at about 450 lb/sq in., 750° F.

In addition to these large units, several pilot plants of 50 to 70-MW output are to be constructed, these will include: a homogeneous heavy-water-moderated thermal breeder working on the U^{233}–Th^{232} cycle; a thermal graphite-moderated sodium-cooled reactor; and a fast sodium-cooled breeder working on the Pu^{239}–U^{238} cycle.

Dr Kurchatov placed high hopes in the water-moderated epithermal reactor and said he believed it had great possibilities for the nearest future. He produced some interesting technical material on these reactors to demonstrate their advantages.

School for Dounreay

The first school in this country, designed specifically to train technicians for atomic power plant work is to be built at Ormelie, Thurso, by the Caithness Education Committee. The architects for the project, which has been approved by the Scottish Education Department, are Basil Spence and Partners, Edinburgh. The school will have special technical sections devoted to the work of training apprentices in atomic energy.

Eight miles west of Thurso lies Dounreay, where the British fast-breeder reactor is being built. Since work began on this project some 18 months ago, Education Authority teachers have been conducting day-release classes in the Dounreay workshops. Here, physics and technical drawing are taught as compulsory subjects while evening classes in Thurso handle mathematics. The possibility of coordinating the new Ormelie school with training for advanced workers in the atomic energy field is being investigated.

Scottish AEA?

The Scottish Council (Development and Industry) recently urged Scottish engineering concerns to investigate the scope for activity in atomic energy—particularly in the instrumentation field. The size of firm was stated to be no criterion for success, provided it has progressive and effective instrumentation ideas to offer and this also applied to firms in the steam and allied fields.

The Council has now completed an assessment of the work which could accrue to Scottish firms in this field, and it shows one major inherent problem—the lack of organisations sufficiently large to undertake this work as individuals. The answer to this is believed to be coordination, cooperation and even for integration of cooperating units. The scarcity of existing labour and the difficulty of recruiting new juniors of sufficient promise make this development hard to achieve and the establishment of a Scottish Division of the Atomic Energy Authority has been urged as one method which would allow speedy and effective development along the lines sought in Scotland.

Pay rise for 15,000

Nearly 15,000 manual workers employed by the AEA at all their establishments are to benefit under a wage agreement recently negotiated between the Authority and the ten unions involved. New uniform national minimum rates and working conditions were agreed. The unions claimed basic rates of £10 and £8.5.0 weekly for craftsmen and labourers respectively, the Authority's proposals being £9.6.0 and £7.13.0. The new agreements were arrived at after demands had been made for strike action.

Scottish reactor urged

The need in Scotland for a nuclear reactor for scientific and clinical research was urged recently by Dr J. M. A. Lenihan, Regional Physicist of the Western Regional Hospitals Board, speaking on "Applications of Atomic Energy in Science and Medicine" in Glasgow.

Many important investigations, said Dr Lenihan, demanded isotopes with half-lives of one hour or less and these must be made on the spot in a reactor. A small reactor could be provided for £150,000–£200,000 and this was not too high a price to pay for a tool which would prove invaluable in many spheres of research.

Fermi patents suit

A writ against the United Kingdom Atomic Energy Authority was recently issued by Philips Electrical Company Ltd, alleging the infringement of certain patents. The patents in question are those originally taken out by the late Enrico Fermi and his associates, amongst whom was Bruno Pontecorvo, and they cover certain fundamental work on uranium fission, done in Rome before the war. These patents later passed into the hands of the Philips Company.

A similar action was brought last year against the United States Atomic Energy Commission and was settled out of court for £300,000.

Harwell open week

During the week ending 2nd June, the Atomic Energy Research Establishment, Harwell, was open to photographers, British and foreign pressmen, Members of Parliament and representatives of the universities. A fully illustrated account of this will appear in next month's NUCLEAR POWER.

commonwealth

Big uranium prospects

In the next ten years the South African uranium mining industry stands to earn about £350m when the present contracts with the US and the UK expire, according to Mr J. Reid, secretary of the Atomic Energy Board, speaking in Cape Town on 8th May. The annual rate of production would reach £50m. On the Rand, 27 gold mines have contracts to produce uranium and 20 are already supplying it.

A committee appointed to investigate a research programme have found that the Cape Town district might be suitable for a nuclear power development, since coal at present comes 1000 miles from the Transvaal.

British capital for Canada

With headquarters in Toronto, a new uranium mining concern, Rio Tinto Mining Co. of Canada, has been formed to work many uranium properties at Blue River, Ontario. One of these, Pronto Uranium, is already providing oxide under a government contract for $55m, while another nearby, Algom Mines, is due to start deliveries valued at $207m later this year.

The new company is the result of a merger of a subsidiary of Rio Tinto, London, with the Hirshom mining group and is said to represent a very big British investment.

Australian D_2O reactor

A research reactor to be built near Sydney is to use about ten tons of heavy water. This would be obtained from America, according to Mr Howard Beale, the Minister of Supply.

soviet union

New Authority set up

The government recently set up a new Central Atomic Energy Board under the directorship of Yefim Slavsky. The Chief Board—as it is known—is charged with developing power reactors and guiding research into other ways of using atomic energy.

In a published interview in *Izvestia*, Mr Slavsky stated that the current five-year plan ending in 1960 would include five nuclear power stations each of 400–600 MW, situated in the region of Moscow, Leningrad, Sverdslovsk and the Urals. He also said that a 16,000-ton, 44,000-h.p. nuclear-powered ice-breaker was already under construction and that power plant for aircraft and surface transport were also being developed.

British power experts visit

A British delegation, headed by Central Electricity Authority chairman Lord Citrine, arrived in Moscow on 17th April at the invitation of Minister of Power Stations, Georgi Malenkov. The British party included Mr J. S. Pickles, Chairman of the South of Scotland Electricity Board, Mr J. Eccles, Deputy Chairman

(Ops.) of the CEA, Mr J. C. Duckworth, the Authority's chief nuclear power engineer and other senior officials of the Authority and regional boards. On 20th April the party spent nearly the whole day at the Academy of Science's prototype nuclear power station near Moscow, where they were shown round by acting director Dr Andrei Krasin and chief engineer A. N. Grigoryants. This plant, it will be recalled, was fully described at the Geneva conference by Prof. D. Blokhintsev. The reactor is a water-cooled heterogeneous type and supplies a 5-MW turboalternator.

On his return, Lord Citrine said he was impressed with the Russian standards of electrical efficiency which compared well with those of the west. An account of the visit by Mr Duckworth will appear in the next issue of NUCLEAR POWER.

Blokhintsev heads new institute

The recently established International Atomic Research Institute is to have full facilities at the Soviet Academy of Science's laboratories—including the great synchophasotron. The institute has at present eleven member states—Albania, Bulgaria, China, Czechoslovakia, East Germany, Hungary, North Korea, Mongolia, Poland, Rumania and the Soviet Union. The member states, all of which have equal rights, elect the director and two deputies, the former for three years and the latter for two. The first director is Prof. Dmitri Blokhintsev, assisted by Dr Marian Donysz of Poland and Dr Vacla Votruba of Czechoslovakia. Besides joint work in Moscow, the member countries are encouraged to set up their own research centres and several particle accelerators and research reactors are being built by the Soviet Union for them. The Soviet government has also recently announced technical cooperation agreements with two non-members—Yugoslavia and Egypt.

West at Physics Conference

A conference on the physics of high energy particles was held in Moscow last month at the P. E. Lebedev Institute of Physics. Scientists from 20 countries attended, the British party including: Prof. R. E. Peierls of Birmingham University, Prof. H. W. Skinner of Liverpool University, and Dr T. G. Pickavance and Dr T. H. R. Skyrme of Harwell. The American delegation of 14 included: Drs Luis Alvarez, Emilio Segré and Owen Chamberlain of the University of California, and Dr Victor Weisskopf of MIT. The conference heard a report on the proposed Russian 50–60-BeV proton synchrotron.

Biggest particle accelerator

The Soviet Academy of Sciences' immense 10-BeV synchophasotron is now nearly complete in its special circular building at the electrophysical laboratory in Moscow. At present the biggest particle accelerator in the world, the phasotron is 200 ft in diameter and weighs 36,000 tons. Speaking in Moscow recently, the chief designer of the phasotron, Dr N. I. Wechsler, referred to the antiproton recently discovered with the 6-BeV Bevatron at Berkeley, California and said he hoped the phasotron would expand these studies and contribute to knowledge of fundamental particles.

Protons from a hydrogen source are first raised to the 9-MeV level in a linear accelerator before entering the phasotron and after about 4½ million circuits—over the distance to the moon and back—have energies of 10 BeV. They then pass through a slit in a 25-ft thick concrete wall to the experimental facilities. The entire apparatus is remote controlled.

The synchophasotron will not hold its title for very long, for the proton synchotron now under construction by CERN at Geneva is designed for energies of about 25 BeV. Even this is not the end by any means, for the Soviets recently announced their intention to build a 50-BeV machine.

east europe

Czech five-year plan

Atomic energy is regarded as an important part of the Czechoslovak five-year economic development programme announced recently. Near Prague an institute of nuclear physics is being built and a pilot power station is scheduled to start operating between 1960 and 1965. The plan includes the building of a plant for the processing of Czechoslovak uranium and for the production of heavy water.

Hungary starting

Work began last month in Budapest on Hungary's first atomic research station. The building of a power station is planned to begin during the next four years and it is hoped to have this in operation in the early 1960s.

scandinavia

Russians steal show

At last month's Swedish Industries Fair in Göteborg, a highlight was the huge Soviet exhibit devoted to atomic energy. The display was considerably bigger than that shown at Geneva and included a model of a proposed 200-MW station that is stated to be under construction in Turkestan. The United States had their travelling exhibition while France showed work on progress on new plants. Britain was not represented as a nation but some British firms showed their products through Swedish agents.

Kjeller reactor uprated

It was announced in Oslo on 4th May that JEEP is to have its output increased from 350kW to 850kW. This will involve changes in the heat-exchange system, but the reactor will not require to be rebuilt.

JEEP is a thermal heterogeneous heavy-water research reactor operated by the joint Norwegian-Dutch atomic energy organisation at Kjeller near Lillestrøm.

united states

Atoms for Peace plan drafted

A draft statute for the proposed International Atoms for Peace Agency was published in New York on 25th April after it had been adopted by the twelve sponsoring nations: UK, USA, USSR, France, Canada, Australia, Belgium, Brazil, Czechoslovakia, India, Portugal and South Africa. Next September, eighty nations will be asked to support this agency which was first proposed by President Eisenhower in December 1953. The draft contains twenty-three articles and proposes a permanent organisation headed by a director general appointed for a term of four

years by the board of governors which will have as permanent members the atomic big five (UK, USA, USSR, Canada, France) together with ten other members chosen on a regional basis by the general conference. A feature of the board of governors is that decisions will be by simple majority, there being no veto rights.

The objects of the agency are "to accelerate and enlarge the contribution of atomic energy to the peace, health and prosperity of the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose." Apart from exchanges of information and technical advice the agency will manage a pool of fissionable material to be contributed by member states and this will be made available to other members with the approval of the board. For this purpose, it will have depots for the storage of fissionable materials and a staff of eight inspectors will be retained for ensuring that the agency's aims are carried out. The permanent staff would be kept to a minimum but would be of the highest technical standard and drawn from as wide a geographical base as possible.

The Agency will be empowered to enter into an agreement with the United Nations, and it is understood that it is intended that it will eventually form one of the special agencies of that body.

AEC steps up on zirconium

The AEC recently placed contracts for 1000 tons of zirconium a year at an average cost of $14m, the contracts to run for five years. Obtained with bids in the region of $6 to $7 a pound, compared with the current United States price of roughly double that figure, the contracts went to: National Distillers Products Corporation, Carborundum Metals Co. Inc. and NRC Metals Corporation. In addition, the Bureau of Mines plant at Albany, Or., is to have its output increased to 300,000 lb a year and the Commission is furthermore to import about 200,000 lb a year from Japan.

To meet the greatly increased demand, the three companies are to expand greatly their production facilities. National Distillers will build a one-million-lb-a-year plant at Ashtabula, Ohio; NRC's new factory will produce 700,000 lb a year at Pensacola, Fla; and the Carborundum works at Parkersburg, W.Va., will have an output of 500,000 lb.

For a time, United States production of zirconium has shown a marked cutback and this was generally assumed to mean that difficulties had been experienced in making alloys entirely suitable for reactor construction. The new contracts indicate that AEC are now confident that these difficulties have been, or are within sight of being, overcome.

Plowden at Shippingport

Nuclear electricity at present-day US costs within ten years, was forecast by AEC chairman Lewis L. Strauss in Pittsburg on 8th May. Mr Strauss was showing his British counterpart, AEA chairman Sir Edwin Plowden round the site of America's first full-scale nuclear power station at Shippingport, Pa. They were accompanied by Admiral Hyman C. Rickover, head of the AEC branch in charge of naval reactors who, it will be recalled, was largely responsible for the first atomic submarine—the USS *Nautilus*.

Mr Strauss admitted that Britain would have competitive power before the US for two reasons: power already costs much more in the UK; America still has vast reserves of natural fuel. Sir Edwin said he understood that the first full-scale Soviet power station "isn't going to operate before 1958 or 1959".

The Shippingport reactor is a pressurised-water plant to develop about 60MW electricity and is part of the AEC power demonstration programme. The nuclear portion is being handled by Westinghouse, while the conventional side is under the control of the Duquesne Light Co, of Pittsburg. A 8½-in. thick pressure vessel internally clad with stainless steel is being made by Combustion Engineering Inc, at Chattanooga and the steam generators are shared between Babcock and Wilcox and Foster Wheeler. Construction of foundations is now complete and the plant is scheduled for operation next summer.

Atomic patents released

The AEC announced in Washington on 6th May that fifty hitherto secret patents are to be published and that they will grant royalty-free licences as part of its programme to make more information available to private industry. The patents cover such processes as the recovery of uranium from waste-metal products, the preparation of chlorides of uranium and a fast-acting reactor control system. AEC-held patents and applications released for licensing now total 935.

In January this year, the McKinney report to the Joint Congressional Committee on Atomic Energy recommended that the Commission announce its complete interpretation of patent provisions relating to private development promptly and not on a piecemeal or case-by-case basis.

"Study atom"—Lodge urges UN

In countries which have not yet completed their industrialisation, atomic power will create many new opportunities to shortcut the development process, according to Henry Cabot Lodge, Jr, chief United States delegate to the UN, addressing the Economic and Social council in New York on 26th April. Mr Lodge was urging the council to explore the possible role of atomic energy in speeding the economic development of countries most needing it and he said, "we can clearly see that nuclear fuel is a tremendous source of new energy and it will be put to use in the lifetime of most of us". The US delegate, backed by several other countries, asked the council to begin now a programme of studies on the economic aspects of atomic energy developments.

Giant carrier to be atomic

The Navy's first nuclear-powered aircraft carrier will have no less than eight reactors and may have a displacement of 80,000 tons, according to testimony given by Rear-Admiral Albert G. Mumma to a Congressional Committee sitting in Washington recently. Forrestal class carriers—the largest in the world—displace only 60,000 tons. Admiral Mumma said that the Navy was aiming at a nuclear-powered task force capable of remaining at sea indefinitely without refuelling.

News of British firms and institutions will be found on pages 91 and 92.

The antiproton

by O. R. Frisch, FRS
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What does the Berkeley discovery mean?

The laws of electrodynamics are "charge-symmetrical": it makes no difference to the behaviour of a closed system if all its positive charges are replaced by negative ones and vice versa. But Nature is not symmetrical: its positive charges are associated with nuclei and in the last resort with protons, while its negative charges take the form of the light-weight electrons which form the outer garments of atoms and the connective tissue of matter.

This asymmetry might be accepted as an accident of creation. But new creation takes place and recognises charge symmetry. In the beta-decay of unstable nuclei, negative or positive electrons appear as the balance of energy demands it, and high-energy photons (gamma quanta) can create pairs consisting of one positive and one negative electron in perfectly symmetric fashion.

Positive electrons (positrons) were discovered in 1932 and soon found to behave in complete accordance with Dirac's theory of 1928. From that theory it had been deduced that electrons can exist in states with negative energy and should indeed tend to drop into such states. The continued existence of electrons with positive energy was explained by assuming that normally all states of negative energy (infinite though their number is) are filled with electrons and thus incapable—according to Pauli's Exclusion Principle—of accepting any further ones. The "creation of an electron pair" occurs when an electron is lifted out of one of its negative energy states to a positive energy value; the hole that is left behaves like a positive charge and is called a positron.

Superficially that "hole theory" is again asymmetrical: electrons are real while positrons are holes. But its consequences are symmetrical and are unchanged if we assume that positrons are real and electrons holes. In recent times a new formalism has been evolved which is itself symmetrical but, unfortunately, not easily represented in physical terms.

Now what about the proton? It does not obey Dirac's equation (*e.g.* its magnetic moment is wrong), and the existence of a similar particle with negative charge—an "antiproton"—is not a direct consequence of an established theory. Indeed no proton theory exists as yet, to match Dirac's theory of the electron in completeness or elegance; but from many attempts the opinion has emerged that any such theory almost certainly must be charge-symmetrical and thus imply the existence of antiprotons. Why, then, has it taken so long to find them?

The reason is that antiprotons are much more expensive than antielectrons, *i.e.* positrons. An electron has a rest energy of 0·51 MeV; an energy of 1·02 MeV, available in many nuclear transformations, is therefore sufficient to create an electron pair. But a proton pair—*i.e.* a proton and an antiproton—requires 1836 times more energy, in proportion to the higher mass of the proton. Such energies became first available in the laboratory when the Cosmotron (the big proton accelerator of the Brookhaven National Laboratory) started work in 1952, but even its 3 GeV (3000 MeV) energy was not enough because part of it is bound to be wasted in each collision (as energy of the centre of mass of the system). But when the Bevatron (the similar but larger accelerator of the Radiation Laboratory at Berkeley, California) started to produce protons with 6-BeV kinetic energy, a determined search for antiprotons was started by a team headed by Professor E. Segré, and that search was successful.

The protons, having a speed 0·99 times that of light, were made to impinge on a target of copper. (All nuclei just offer a loose cluster of neutrons and protons to such a fast missile; but copper is cheap, dense and easy to cool.) When a proton pair is created most of the energy of the missile is used up and all the four particles—the missile, the proton or neutron struck, and the newly created proton and antiproton—move forward together at about the speed of the centre of mass of the system, about 0·8 times the speed of light. But the same magnetic field which guides the protons on their circular path while they are being accelerated will bend the negatively charged antiprotons outwards, and a special tunnel was provided to allow them to pass through the heavy shielding wall to the laboratory beyond. Large numbers of pi-mesons also emerge from the same tunnel, but they have to be much faster to suffer the same magnetic deflection. So in order to identify the occasional antiproton one had to check the velocity of each recorded particle, and two independent checks were made to make doubly sure. The first one was like a speed trap; two policemen (scintillation counters) with stopwatches (electronic timing devices accurate to better than 10^{-9} sec), spaced out along the path of the particles. The other depended on the phenomenon of Cherenkov radiation: a charged particle, travelling through a transparent medium faster than light travels in the same medium, produces an "optical bow wave", a cone of light whose opening angle depends

LAST year, a research team at the radiation laboratory of the University of California, working under Professor E. Segré, discovered the antiproton. The existence of this particle had been suspected for some years on theoretical grounds, but until the 6 BeV energy of the Berkeley Bevatron became available they had never been observed. The experiment consisted in bombarding the copper target with a beam of protons travelling at a velocity of 0·99 times that of light. This creates some proton-antiproton pairs and a technique was developed for trapping the antiprotons which are, however, created only very infrequently. In this article Professor Frisch examines some of the philosophical implications of this discovery.

UNE équipe de recherches travaillant sous la direction du Professeur E. Segré au Laboratoire de Radiations de l'Université de Californie a découvert l'année dernière l'antiproton. Pour des raisons théoriques on a soupçonné depuis quelque temps l'existence de cette particule, mais on n'a pas pu l'observer avant que l'énergie de 6 BeV du bévatron de Berkeley devint disponible. L'expérience consistait à bombarder une cible de cuivre d'un faisceau de protons se propageant à une vitesse égale à 0,99 de celle de la lumière. Ceci engendre quelques paires proton-antiproton; on a développé une technique permettant d'intercepter les antiprotons; néanmoins, leur naissance est un phénomène bien rare. Prof. Frisch analyse dans cet article quelques conséquences philosophiques de cette découverte.

EINE unter der Leitung von Prof. E. Segré im Strahlungslaboratorium der Universität von Kalifornien arbeitende Forschungsgruppe hat in vorigem Jahre das Antiproton entdeckt. Man hat seit einiger Zeit die Existenz dieser Partikel aus theoretischen Gründen vermutet, doch ist sie nie beobachtet worden, bevor die Energie von 6 BeV des Berkeleyschen Bevatrons zur Verfügung stand. Der Versuch bestand darin, dass ein Kupfertarget von einem Protonenbündel, welches mit einer Geschwindigkeit von 0,99 Lichtgeschwindigkeit sich fortpflanzte, bombardiert wurde. Unter diesen Umständen wurden einige Proton-Antiproton-Paare erzeugt; es wurde eine Auffangtechnik für Antiprotonen ausgearbeitet, doch ist die Entstehung von Antiprotonen eine recht seltene Erscheinung. Prof. Frisch untersucht in diesem Aufsatz einige philosophische Folgerungen dieser Entdeckung.

EL ANO pasado una comisión de investigadores, trabajando en el laboratorio de la Universidad de California bajo la dirección del Professor E. Segré, descubrió el antiprotón. Teóricamente, se habia sospechado por algunos años que esta particula existia, pero no se habian notado antes de la disponibilidad de la energía BeV 6 del Berkeley Bevatron. El experimento consistia en bombardear el blanco de cobre con un rayo de protones que se trasladan a una velocidad de 0·99 veces la de la luz. Esto produce algunas parejas de protones-antiprotones, y se ha desarrollado una técnica para atrapar los antiprotones que son, sin embargo, creados infrecuentemente. En este articulo el Profesor Frisch analiza algunas de las implicaciones filosóficas de este descubrimiento.

ИССЛЕДОВАТЕЛЬСКИЙ коллектив, работающий в лаборатории излучения калифорнийского университета под руководством проф. Е. Сегре, открыл в прошлом году антипротон. Существование этой частицы подозревалось за несколько последних лет по теоретическим соображениям, но наблюдать ее можно было впервые, когда стала доступна энергия берклейского беватрона в 6 Бэв. Эксперимент состоял в том, что медная мишень бомбардировалась пучком протонов, движущихся со скоростью, равной 0,99 скорости света. В этих условиях возникает некоторое количество пар протон-антипротон; разработана техника улавливания антипротонов, которых возникновение происходит, впрочем, очень редко. В этой статье проф. Фриш исследует некоторые философские последствия открытия антипротона.

on the speed of the particle. By accepting only light within a narrow range of angles one records only particles within a certain velocity range. In this way Segré *et coll.* were able to observe antiprotons although they came only about once an hour and were outnumbered about 100,000 to one by pi-mesons.

How can one be sure they are antiprotons? In the first place the mass is right, equal to that of the proton within the expected accuracy of a few per cent. But to be sure one has to observe annihilation: the transformation of the antiproton and some ordinary proton into lighter particles and radiation. Positrons were long ago shown to suffer annihilation on passing through matter, when the joint rest energy (1·02 MeV) of a positron and an electron appear as two (or sometimes three) quanta of electromagnetic radiation (gamma quanta). An antiproton, on being annihilated, would produce 1·9 GeV of energy, mostly not as gamma quanta but as pi-mesons (they may be considered as quanta of the nuclear field which, for a proton, is much stronger than the electromagnetic field). Only a few antiprotons have yet died under the scrutiny of a physicist, but there seems to be no doubt that they do suffer annihilation and thus must be true antiprotons and not some brand-new particle which happens to have a mass close to that of a proton.

What is the significance of this discovery? In the first place it supports the assumption of charge symmetry, an assumption without which a theory of the proton would be even more difficult to make. Secondly, the study of the production and annihilation process, now eagerly pursued by several teams, should soon provide us with important information. Several antiprotons have been seen being annihilated inside a nuclear emulsion or a Cherenkov counter, but the accumulation of evidence is bound to be slow, with a total supply of some twenty a day. Yet some significant results have already emerged. Thus it appears (and this had been suspected before, on indirect evidence) that all processes in which proton pairs are involved happen much more rarely than current theory predicts. That, by the way, helps to explain why antiprotons had not been previously found in the cosmic radiation. The knowledge that they exist has now encouraged a fresh search, and a few were found; but the main source will be the Bevatron until an even bigger proton synchrotron can take over. One such is nearing completion in the USSR.

Yet ordinary matter is charge-unsymmetrical, being made from positive protons and negative electrons. This might be a purely local feature: other galaxies might be made of inverse matter, consisting of antiprotons and positrons (and antineutrons, having the opposite gyromagnetic ratio as ordinary neutrons). That might be very difficult to decide because by spectroscopic study no difference can be detected. Interpenetration of galaxies of the opposite kind would occasionally occur and the annihilation of the interstellar matter (stars practically never collide) would result in unusual brightness; but since collisions between galaxies are anyhow very rare this might have been overlooked. No cosmology has yet been proposed which would lead to the presence of large amounts of inverse matter. If it originated in one big explosion the universe must have been very dense at first, and annihilation would have weeded out all but one kind of matter. If we accept the hypothesis of continuous creation we must find some reason why only one kind of matter is created.

Now, for the first time, it is possible to give full details of the British method of extracting plutonium from irradiated fuel elements

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Primary separation plant at the Windscale Works

Natural uranium consists essentially of two isotopes, uranium 238 and uranium 235, which are present to the extent of 99·3 per cent and 0·7 per cent respectively. Of the two constituents, uranium 235 is fissionable under the conditions which obtain in a reactor, and a chain reaction is set up. The products of the fission of uranium 235 are: considerable heat, neutrons and a mixture of some thirty chemical elements located towards the middle of the Periodic Table which, collectively, are called fission products. Of the neutrons emitted, some are used up in maintaining the chain reaction and others are available for absorption in uranium 238, giving, as an ultimate product, a new element plutonium.

From the composition of the natural uranium it will be seen that the relative quantity of uranium 235 present is small and, in practice, only a fraction of this undergoes fission. In a natural or slightly enriched uranium reactor, for every atom of uranium 235 consumed, approximately one atom of plutonium is formed and it follows that the irradiated material discharged from the reactor will consist largely of unchanged uranium and, associated with it, small quantities of fission products and plutonium.

Plutonium metal is the ultimate primary product from Windscale Works which, as originally designed and constructed, comprised two natural uranium reactors and the associated chemical plant. The plant required to produce plutonium must operate under highly radioactive conditions and be capable of extracting hundreds of grams of plutonium from tons of uranium. Fig. 1 shows the general arrangement of the main plants associated with the chemical process. The irradiated uranium rods are first processed in this plant which, because of the high gamma radiation associated with the fission products, must be heavily shielded. Separation of uranium, plutonium and fission products is effected by a solvent extraction process. The plutonium solution produced is still associated with some uranium and fission products, but the concentration of the latter has been reduced to a point at which further processing can be done without heavy shielding. In the second stage of the process the final traces of uranium and fission products are removed, leaving a very pure solution of plutonium nitrate. This solution is transferred to the metal finishing plant, where it is converted to plutonium metal. The three processes, although carried out in

PLUTONIUM is manufactured in Britain in the two air-cooled, graphite-moderated piles of the Windscale works of the United Kingdom Atomic Energy Authority. After removal from the piles the irradiated fuel rods are first stored under water for several weeks. They are then dissolved in nitric acid and the solution passed through three towers from which streams of fission products, plutonium and uranium are obtained by solvent extraction with dibutyl carbitol. The plutonium and uranium streams undergo further purification while the fission products are concentrated and stored. The plant has a highly active section and a moderately active one and although it was at first doubted whether access even to the medium active cell would be possible, methods have since been developed for achieving this. Full details of the process are given, and some of the operational problems discussed.

LE PLUTONIUM est fabriqué en Grande-Bretagne dans deux piles réfroidies à l'air, avec modérateur graphite, faisant partie de l'usine de Windscale appartenant à l'Administration d'Energie Atomique au Royaume-Uni. Après avoir été enlevées des piles, les barres du combustible irradié sont d'abord emmagasinées sous l'eau. On les dissout ensuite dans de l'acide nitrique, et la solution obtenue passe à travers trois tours, d'où des courants contenant les produits de la fission, plutonium et uranium sont obtenus par l'extraction avec le solvant dibutylcarbitol. Les courants contenant plutonium et uranium subissent des procès de purification supplémentaires, tandis que les produits de la fission sont concentrés et emmagasinés. L'usine a une section de très haute activité et une autre d'activité modérée. Quoiqu'on ait douté d'abord de l'accessibilité même de la section d'activité modérée, ceci a été rendu possible par des méthodes développées depuis. L'article donne des détails sur le procesus, et quelques problèmes d'exploitation y sont discutés.

PLUTONIUM wird in Grossbritannien in zwei luftgekühlten und mit Graphitmoderatoren versehenen Reaktoren des der Atomenergiebehörde Grossbritanniens gehörenden Windscale-Werkes hergestellt. Die aus den Reaktoren herausgenommenen bestrahlten Brennstoffstangen werden zuerst einige Wochen lang unter Wasser aufbewahrt. Sie werden dann in Salpetersäure aufgelöst, worauf die Lösung durch drei Türme geleitet wird, aus welchen Ströme von Spaltungsprodukten, Plutonium und Uran durch Extraktion mit dem Lösungsmittel Dibutylkarbitol erhalten werden. Die Plutonium- und Uranströme werden weiteren Reinigungsprozessen unterworfen, wogegen Spaltungsprodukte konzentriert und aufbewahrt werden. Die Anlage hat eine äusserst aktive und eine mässig aktive Zone; obwohl man zuerst zweifelte, ob es überhaupt möglich wäre, sogar die mässig aktive Zone zugänglich zu machen, hat man inzwischen die diesbezüglichen Verfahren ausgearbeitet. Der Prozess wird umständlich geschildert, und einige Betriebsprobleme werden erörtert.

EL PLUTONIO es fabricado en la Gran Bretaña en dos pilas enfriadas por aire, moderadas por grafito, en la instalación en Windscale de la Autoridad de la Energía Atómica del Reino Unido (U.K. Atomic Energy Authority). Una vez retiradas de las pilas, las barras del elemento combustible irradiado son mantenidas bajo agua durante varias semanas. Entonces son disueltas en ácido nítrico y la solución es pasada por tres torres que producen chorros de materias de fisión, plutonio y uranio por extracción con solvente, utilizándose el dibutilo carbitol. Los chorros de plutonio y uranio se purifican aun más, mientras que las materias de fisión son concentradas y almacenadas. La planta tiene una sección de alta actividad y otra de actividad moderada, y aunque se dudaba al principio si sería posible tener acceso aun a la célula de actividad media, ya se han desarrollado métodos de efectuarlo. Se dan detalles completos del proceso, y se debaten algunos de los problemas de operación.

В ВЕЛИКОБРИТАНИИ плутоний получается в двух котлахе воздушным охлаждением и графитовым замедлитем, находящихся в Уиндскэйльском заводе Великобританского Управления Атомной Энергией. После удаления из котлов, облученные стержни горючего хранятся сначала под водой. Потом их растворяют в азотной кислоте и раствор пропускают через три башни, из которых струи продуктов деления, плутония и урана получаются путем извлечения растворителем дибутилкарбитм. Струи, содержащие плутоний и уран, подвергаются дальнейшей очистке, в то время как продукты деления концентрируются и хранятся. На заводе имеется одна очень активная часть, и другая, умеренно активная. Хотя вначале сомневались в возможности доступа даже к умеренно активной части, в последствии были разработаны методы, позволяющие осуществить эту цель. В статье даются детали процесса и обсуждаются некоторые вопросы эксплуатации.

separate buildings, really form one integrated process in which the plutonium-bearing side streams from the two latter processes are fed back to the Primary Separation Plant, thus achieving maximum plutonium economy.

The solution of uranium depleted in uranium 235 is purified by a further solvent extraction process and is returned as a pure solution of uranyl nitrate to the Springfields Works, where it can be either blended with enriched uranium to restore the uranium 235 content or converted to hexafluoride for processing in the diffusion plant at Capenhurst.

The main fission product stream is concentrated by evaporation and then stored underground in heavily shielded tanks.

The solvent used in the extraction processes was initially purified by distillation before being recycled. Distillation has now been replaced by a multi-stage washing process which achieves the same results at greatly reduced cost.

The various side streams containing small amounts of fission products are delivered to temporary storages and are eventually passed through a conventional effluent treatment plant where the greater part of the activity is absorbed on a precipitated floc. After filtering, the filtrate which has a very low specific activity, is pumped to sea through pipelines that extend nearly two miles from the shore.

Designed for simplicity and continuity

It is well known that the fundamental research on the chemical process was done on some twenty milligrams of plutonium and this, in itself, was an achievement. The results of the work indicated that a separation of plutonium, uranium and fission products was possible by the use of certain organic solvents since, according to their valency state, uranium and plutonium are preferentially soluble in an organic solvent or aqueous solution. Numerous solvents were investigated and finally dibutyl carbitol was chosen.

Because some of the solutions would be intensely radioactive and therefore the plant would have to be operated remotely, it was decided that simplicity would be the essence of the design. The conception of continuous operation was adopted and the extraction would be carried out in simple packed columns. Also, glanded equipment such as pumps would be avoided and the design would be based on gravity flow. The flow diagram is given in Fig. 2.

Irradiated rods, after discharge from the reactors, are stored under water for several weeks. The reason for this is that an appreciable proportion of the mixed fission products in the rods have half-lives of less than ten days and for all practical purposes they will have decayed completely in about a hundred days. Thus the total radiation associated with an irradiated uranium rod immediately after discharge from the reactor will have been reduced by a factor of two or three in a period of two months. There is no advantage in extending the "cooling" period beyond eight weeks, since after this time the rate of reduction of total activity decreases rapidly.

After cooling, the rods are charged into a dissolving unit. Nitric acid is metered to the dissolver and reacts with the rods to give a solution of uranium, plutonium and fission-product nitrates. The reaction is strongly exothermic and after initiating by steam heating it is self-sustaining. The oxides of nitrogen evolved during the reaction

are mixed with oxygen and are absorbed as nitric acid by the incoming acid feed. This simplifies the control of the dissolving process and achieves complete utilisation of nitric acid. Any incondensible gases, including radioactive inert gases, pass through a caustic-soda scrubbing system and are eventually discharged to atmosphere from a stack the top of which is four hundred feet above ground-level. The hot rod solution overflows continuously from the dissolver into a jacketed stirred vessel where it is cooled to the required temperature and its composition adjusted to that required for optimum extraction conditions in the first column.

The conditioned solution is metered at the required rate into the centre of the first extraction column, the lower half of which constitutes the extraction section. The rod solution flows counter-current to a conditioned solution of dibutyl carbitol which is introduced at the bottom of the column. Both the uranium present as uranyl nitrate and plutonium as tetravalent plutonium nitrate are preferentially extracted by the solvent, leaving most of the fission products in the aqueous phase. The latter, containing only a very small percentage of uranium and plutonium, flows out from the base of the column and passes to a separate plant where its volume is reduced by evaporation and the concentrated solution is put into permanent storage. To a very small extent, fission product nitrates also dissolve in the solvent phase and a further decontamination from these is effected in the top half of the column, called the stripping section. The solvent in this section flows counter-current to a solution of nitric acid. The solvent stream containing uranium, plutonium and still traces of fission products flows out at the top of the column.

Reducing plutonium to trivalent state

In order to separate the plutonium from the uranium, the plutonium must be reduced to the trivalent state, and to do this the solvent solution from the first column is mixed with a selected reducing agent in a series of stirred vessels. The uranyl nitrate remains unaffected by this treatment, but the trivalent plutonium nitrate becomes preferentially soluble in aqueous solutions.

The reduced solution is metered and introduced at the centre of the second column. This also is a composite column. A stream of conditioned aqueous solution introduced near the top extracts the plutonium from the solvent phase rising through the column. This aqueous extract of plutonium nitrate is stripped of uranium by a solvent stream introduced at the base of the column.

The solvent phase from column No. 2, which contains practically all the uranium, is introduced near the base of column No. 3 through which it rises counter-current to an aqueous stripping solution. In this column the acid concentration is such that the uranium is extracted completely into the aqueous phase. The aqueous solution of uranyl nitrate is concentrated by continuous evaporation before dispatch to another plant, where it undergoes a further purification process in order to remove the very small quantities of plutonium and fission products still associated with it.

Final concentration by evaporation

The aqueous extract from the second column also contains some uranium and traces of fission products and is given a purification cycle in columns No. 4 and 5. In order to do this, the plutonium has to be reoxidised to the tetravalent state by mixing with an oxidising agent in stirred vessels. The resulting plutonium solution is introduced at the centre of column No. 4, where it is extracted into the solvent phase which in turn is stripped by an aqueous solution in the top half of the column. The composition of the aqueous phase in this column is carefully controlled to ensure the preferential extraction of fission products into this phase. The solution leaving the base of the column is sent to storage tanks in which it is held for some time to allow for a certain amount of radio-active decay. Subsequently it passes to the Effluent Treatment Plant and after treatment is discharged to sea.

The solvent solution of plutonium nitrate is introduced near the base of column No. 5 through which it flows counter-current to a conditioned aqueous solution. The composition of the stripping solution is adjusted to ensure maximum extraction of plutonium into the aqueous phase. Finally, the solution of plutonium nitrate is concentrated in batch evaporators and then transferred to a purification plant, where the final traces of uranium, fission products and certain metallic ions are removed.

The solvent streams leaving columns No. 3 and 5 are collected and given a series of washes. In this way, traces of fission products, plutonium and uranium are removed and a substantially inactive solvent is made available for re-use in the process.

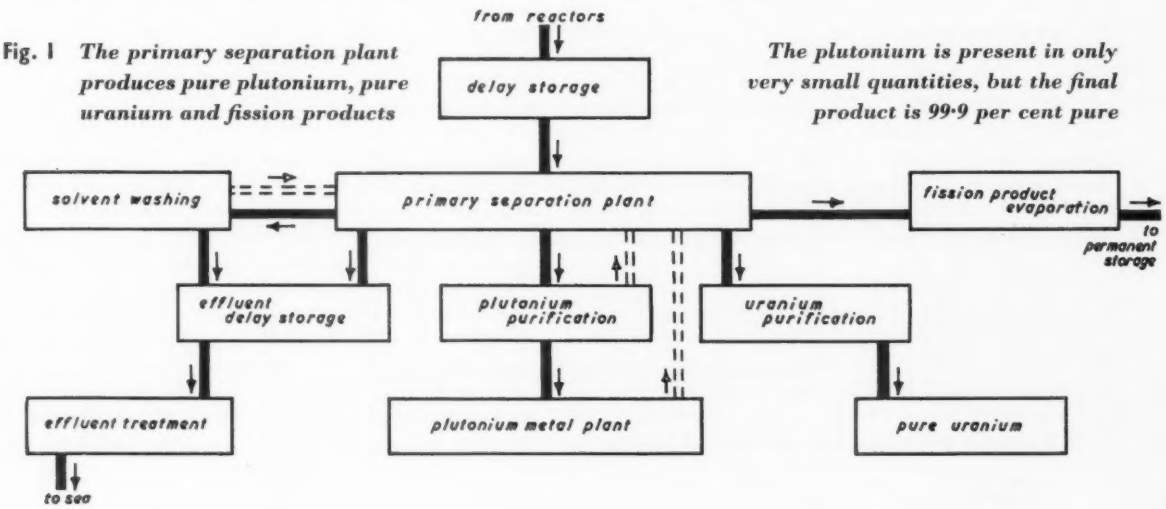


Fig. 1 ***The primary separation plant produces pure plutonium, pure uranium and fission products***

The plutonium is present in only very small quantities, but the final product is 99·9 per cent pure

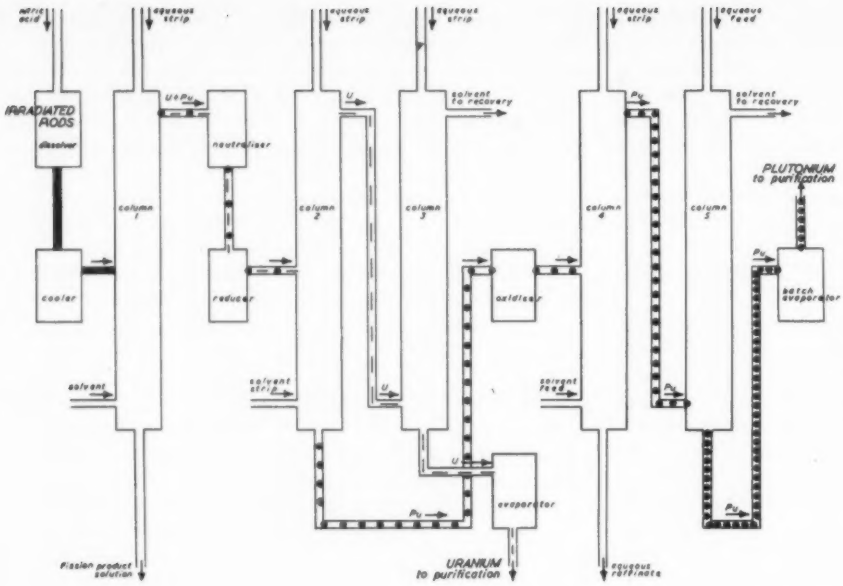


Fig. 2
The separation process is continuous and is carried out by solvent extraction in simple packed columns. Columns 1, 2 and 3 produce the main streams, whilst the plutonium stream from column 2 is given further purification in columns 4 and 5

The nature of the material to be processed obviously needs some departure from the normal methods of plant design and operation. The fission products after the prescribed cooling period are still intensely beta- and gamma-active and each ton of irradiated uranium to be processed has associated with it tens of thousands of beta-gamma curies. For this reason the whole of the plant in contact with active solutions is enclosed in a concrete box which serves as a radiation protection shield for the operational area that surrounds it. As the majority of the fission products are removed in the first extraction column the active plant is subdivided into areas of high and medium activity. The thickness of shielding required for the highly active section is of the order of three feet, while a thickness of one and a half to two feet is adequate for the medium active section.

Complete duplication of plant

At the design stage it was assumed that once the plant went into operation it would be impossible to reduce the level of activity in the highly active cell to a point which would make access possible for repairs and maintenance to be carried out. Consequently the principle of 100 per cent spare capacity was adopted and two highly active cells were proposed to serve one medium active cell. Similarly, access to the medium active cell was considered to be extremely doubtful and therefore two complete units were built, each comprising one medium active cell and two highly active cells. The broad layout of the plant thus consisted of a concrete box containing two complete units, the box being surrounded by an inactive operational area. This is shown diagrammatically in plan and elevation in Fig. 3.

In addition to protection from beta-gamma radiation, it is also essential to take precautions to ensure that even minute quantities of the active liquors do not escape into the operational areas. Plutonium is an emitter of alpha radiation and if it is inhaled or ingested it can be absorbed in the body structure with detrimental effect. A similar argument applies to beta-gamma emitting fission products. Therefore all necessary steps must be taken to prevent personnel inhaling or ingesting such radioactive materials. The stringent regulations are illustrated by the fact that the maximum permissible levels of contamination of air by alpha or beta-gamma emitting materials are; alpha, 10^{-12} curies/m^3; beta-gamma, 10^{-9} curies/m^3.

For the specific case of plutonium, this means that the maximum permissible concentration in air is 6×10^{-4} micrograms/m^3.

Rod handling under water

To avoid the possibility of escape of even the most minute quantities of active materials all vessels inside the concrete shield are sealed and maintained at a negative pressure with respect to the cell, and in turn the cell is kept at a negative pressure with respect to the operational area. Thus the air flow is from the operational area into the cell and the air inside the cell is heated and controlled to maintain a constant temperature.

The irradiated rods are transferred from the reactor cooling ponds in heavily shielded containers. These are hoisted to the top operating floor of the separation building and immersed under water in a rod charging pond. This pond forms a projection from the highly active shielded wall inside which is located the dissolving unit. The rods are removed from the container under ten feet of water which acts as a complete radiation shield for the operator and at the same time, with special underwater lighting equipment, offers adequate visibility (Fig. 4). By using pivoted tongs the rods are fed into a hydraulically operated machine which, through a specially designed chute, charges the rods through the main shield wall into the dissolving unit. The plant installed inside the concrete shield is unique in several respects because it was assumed that maintenance would not be possible. As pointed out previously there are no valves or pumps or other glanded equipment, and moving parts were reduced to the absolute minimum. The principle of gravity flow accounts for the height of the building, but it is worth pointing out that the principle was not achieved entirely and there are a

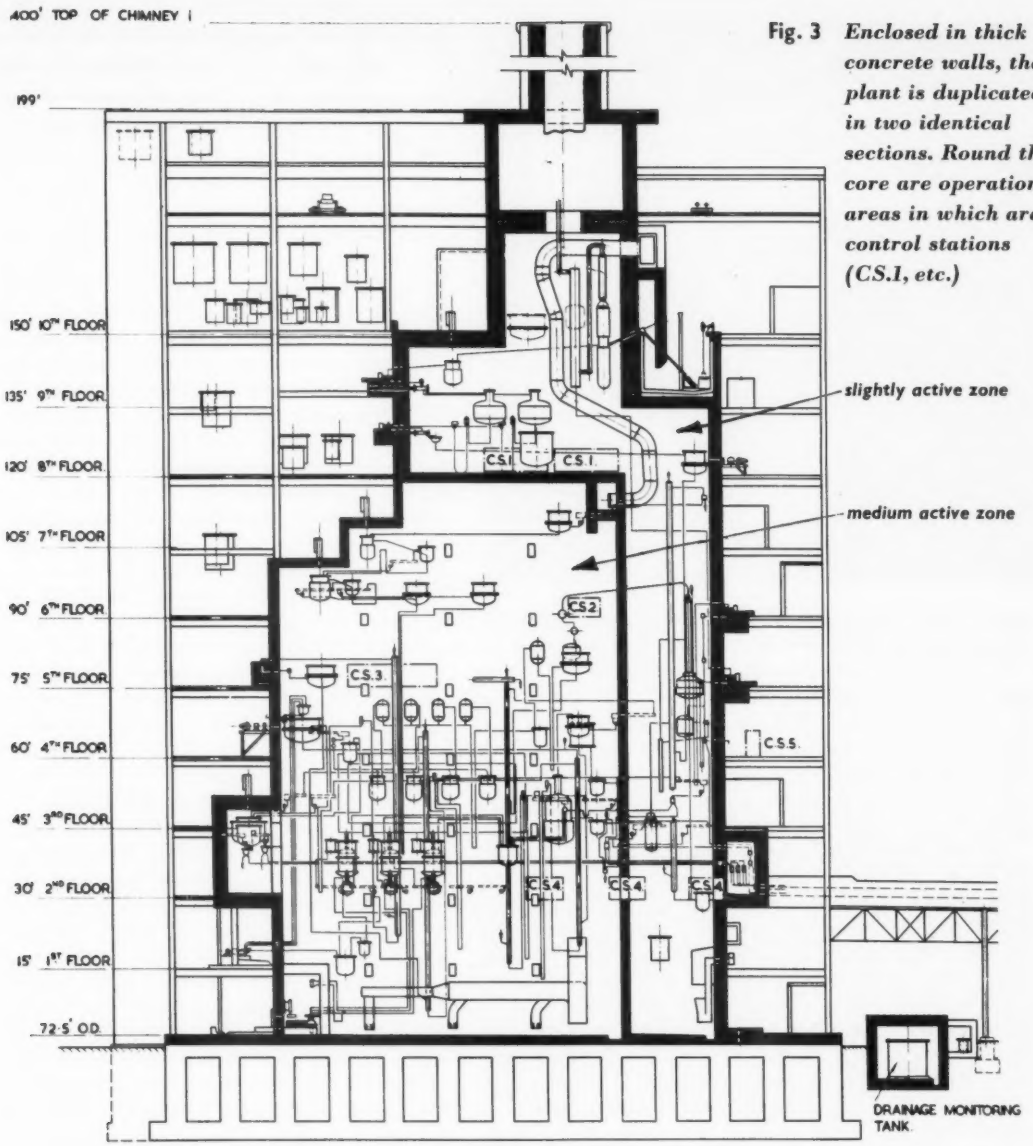
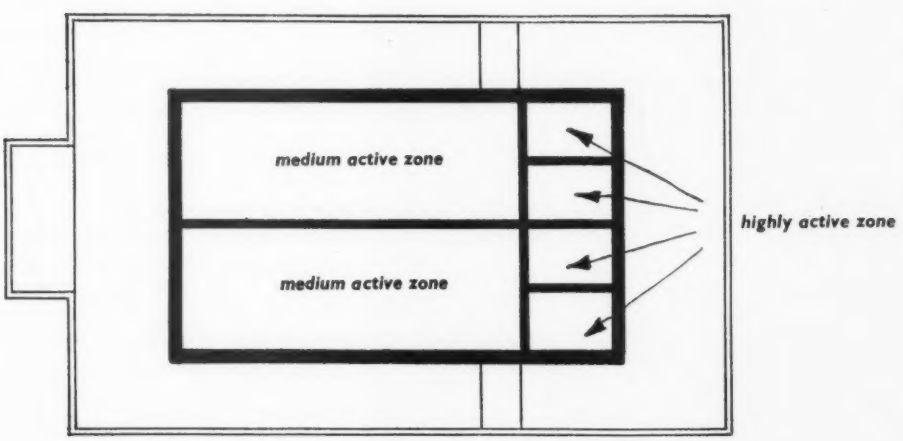


Fig. 3 ***Enclosed in thick concrete walls, the plant is duplicated in two identical sections. Round the core are operational areas in which are control stations (CS.1, etc.)***



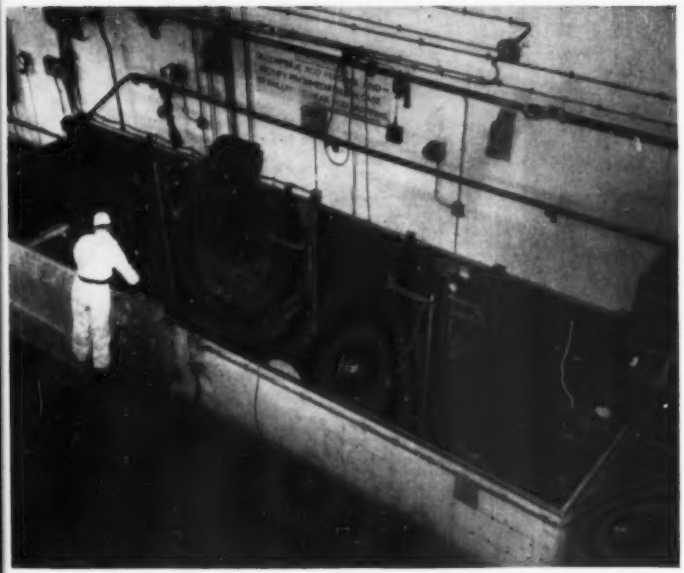


Fig. 4 ***Special containers, raised by lift to the top of the building, convey irradiated rods from the cooling pond. They are then unloaded under 10 ft of water and fed to the rod dissolvers***

small number of points at which liquors are lifted by vacuum generated by a steam ejector through a series of vessels associated with the necessary lute lines. The active plant is of all-welded construction and is fabricated entirely from a fully austenitic 18/13/1 stainless steel. It was essential to ensure the highest possible quality of welding and all welds were visually inspected and x-rayed. An indication of the arrangement of vessels and flow of materials is given in Fig. 3.

The only moving parts associated with the active plant are stirrers and flow-measuring devices. The stirrers are of the simple paddle type and are driven by a motor located in the operating area. All stirred vessels are located under steps in the shield wall through which the stirrer shaft is introduced. The shaft is surrounded in the shield wall by a removable stepped shield plug and if necessary the stirrer can be removed for maintenance. The equipment for measuring flow is a simple adaptation of the ancient Egyptian irrigation wheel. It consists of a number of small barrels connected by radial arms to a central hub. The hub is attached to a shaft which runs in a stepped bearing housed in the shield wall. It is driven by a constant-speed motor located in the operating area and the motor is therefore available for maintenance. On rotation, the barrels, which are hollow and have a hole in one end, dip into a reservoir of the liquor to be metered and pick up an accurately known constant volume which by rotation is delivered through the hollow radial arms to a tundish which collects the liquor and allows it to flow to the next stage of the process. Volume measurements throughout the active plant are made by measurement of the depth of liquor in vessels which have been accurately calibrated. The depth of liquor is determined by pneumercators which by being arranged in pairs also give a measure of the specific gravity. A similar device based on the differing specific gravity of the solvent and aqueous phases has also been adopted to stabilise the interface in the extractors.

An important feature of the plant design are the process control points, there are a considerable number of these (a typical arrangement is shown diagrammatically in Fig. 5), each being housed in a projection to the shield wall. Where measurements or the taking of samples for process control are necessary the whole flow of liquor is piped through the shield wall and discharged into a long, narrow trough through which it flows and then returns through the shield wall to the next part of the process. The trough is embedded in the concrete bulge and is covered by a shield consisting of a stainless-steel lead sandwich. As the hold-up volume in the trough is small the shielding required is less than that for the main shielded wall. Equipment is located over the troughs, which enables samples to be taken and also measurements to be made of temperature, specific gravity, acidity, and alpha and beta-gamma radiation.

Temperature measurements of liquors inside the cell are made by means of thermocouples. These and the associated wires are enclosed in an all-welded sheath built into the shield wall so that the thermocouples can be withdrawn for checking or replacement.

The solvent used in the process has a comparatively high flashpoint and the chances of ignition are small. However, the consequences resulting from a fire in the active cells would be serious, and for this reason an extensive fire-prevention system which is entirely automatic was incorporated in the structure. A series of detectors distributed throughout the cell are connected to a battery of carbon dioxide cylinders. A signal from any one detector causes the base of the cell to be flooded with water, thus sealing off the ventilation air intake and at the same time filling the cell with carbon dioxide. Additionally, a manually operated foam system is installed over the solvent tanks in the operating area.

The foregoing items are only a few taken at random, but they are sufficient to indicate the approach which is necessary in dealing with processes of this nature.

The inactive plant located in the operational area is concerned with the preparation of the various inactive solutions which are used in the process. This plant is quite conventional and needs no special comment (Fig. 6 shows a typical arrangement).

Controlling the processes

Operational control of the process is exercised from a number of stations located at various levels throughout the building. Each station serves a number of plant items. The inactive reagents used in the particular section are metered into the plant by means of rotameters mounted at the station. Steam heating and water cooling of process vessels are also controlled from this point. The dials and recorders associated with the relevant instruments, located both at instrument troughs and, in the case of temperature and depth measurement, inside the shield, are mounted in a panel which also contains the column interface controls and the control for the variable-speed motor which drives the constant-volume feeder (Fig. 7 shows a representative control station).

Fortunately each main constituent of the active material being processed has a characteristic property which greatly facilitates measurement and control. Uranyl nitrate,

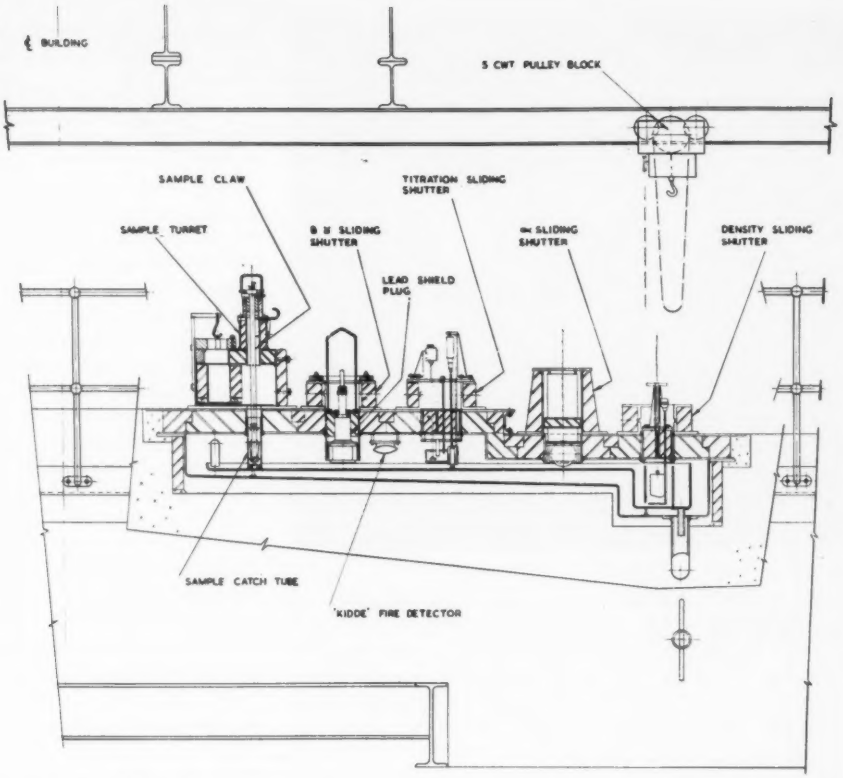


Fig. 5 ***Many process control points are situated throughout the plant. Liquors are brought through the shield wall into a trough protected by a stainless steel-lead sandwich. Here, samples are taken and measurement made***

which is present in bulk in the early stages of the process, forms a solution with comparatively high densities. Thus an accurate determination of the density of uranium-bearing streams gives a good indication of the uranium content. An adaptation of the Nicholson hydrometer is mounted in one section of the instrument trough and gives a continuous measurement of specific gravity which, together with the temperature of the liquor, is relayed to the control panel. Plutonium is intensely alpha-active, one microgram of the element emitting over a hundred thousand alpha-particles per minute, and therefore the counting of alpha-particles is the method of control. Since alpha-particles have only a very short range in air the alpha-counting equipment must be mounted close to plutonium-bearing liquors. To prevent alpha contamination of and also damage to the meter by acid vapour, it is essential that the quantity of liquor presented to the instrument shall be small while still maintaining a constant surface area. Both these conditions are met by rotating a stainless-steel drum on the surface of the liquor running through the trough. The thin film of liquor thus picked up is presented to a scintillation counter. A standard alpha source of plutonium is shown to the counter alternatively with the film of liquor on the drum and thus a constant check is obtained. Liquors which have a relatively high plutonium content are measured and a direct reading is transmitted to and recorded at the control station. In the case of raffinate streams from which plutonium has been extracted the alpha measurements are automatically integrated for any desired period and thus an accurate determination and a control of plutonium losses are achieved. Fission products which are beta- and gamma-active can be estimated by direct measurements using a Geiger counter. Unfortunately, equipment used in connection with active solutions tends to pick up a background of beta-gamma activity which often exceeds the specific gravity of the liquor being counted and this has considerably restricted the use of this type of instrument.

Although there is extensive use of instruments in the process, ultimate control and material accounting depend on analytical data. Samples for analysis are taken from the control points by means of special equipment called sam-

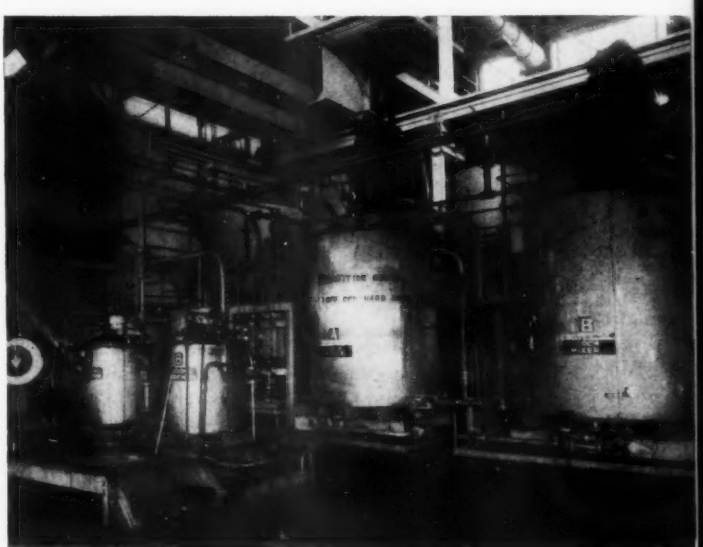


Fig. 6 ***Inactive plant for the preparation of process solutions is of conventional design and is located in the operational areas***

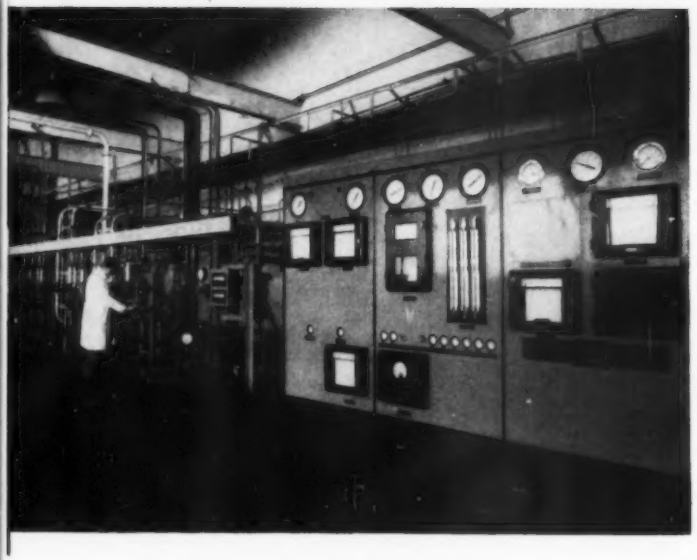


Fig. 7 ***Control stations are situated at various levels. Here, inactive reagents are metered and the heating and cooling of process vessels controlled***

pling turrets which are mounted directly over the liquor in the trough. A small pipette with an attached rubber bulb is used for taking the sample and a special mechanism permits of the sample being taken and loaded into a container which is an effective shield entirely by remote operation. The container is withdrawn from the turret and transferred to the laboratory.

The laboratory in which the samples are analysed is specially designed for the handling of radioactive materials. Heavily shielded cubicles provided with remotely controlled handling equipment and lead-glass observation ports are used for dispensing and analysing highly gamma-active samples, while cabinets which have been evolved from the traditional fume cupboard are used for dealing with alpha and low beta-gamma activity samples. Obviously full use is made of radioactive properties of the materials and radiometric determinations form the basis for a considerable proportion of the work. However, absorptiometric, spectrographic, x-ray, infra-red, polarographic and conventional volumetric and gravimetric methods are also extensively used.

Dangers of special clothing

The analytical work carried out can be divided broadly into three main sections.

Plant control demands an analytical service to ensure that the process is being operated at the specified efficiencies and that intermediate and final products are of the required purity. These analyses also form the basis of the frequent plutonium mass balances that are carried out. The mass balance is extremely important in processes which are handling fissionable materials, since critical masses of such materials must not be allowed to build up in any part of the plant.

It has been mentioned that the work on which the process was established was done on twenty milligrams of plutonium. Inevitably, this meant that certain aspects could not be fully investigated and since the Windscale plant has been in operation a considerable analytical effort has been devoted to the study of the various stages and as a result minor improvements have been made to the original flowsheet.

The laboratories have carried out researches in the chemistry of plutonium and evolved new analytical techniques and methods applicable to radioactive materials.

In the operation of a process of this type the overriding consideration must be the protection of personnel from the hazards inherent in the process. When the Works was being planned and designed, was there no practical experience and the initial approach to safety was to confine the chemical plants and their ancillaries within a fence, so that they constituted a group, entry to and exit from which would be through a specially constructed change-room. All personnel on entering or leaving the group would do a complete change of clothing.

After the plant had been working only a few months, it was realised that to rely on special clothing for the protection of the individual in all circumstances is fundamentally wrong and potentially dangerous. Such clothing can give a man a false sense of security, in that he may place in it a reliance which is unjustified, and the principle was established that plant must be designed and operated in such a way that the plant itself protected the individual. Broadly speaking, this is now the approach. The extent to which the principle has been achieved during normal operation can be gauged from Fig. 7, where an operator can be seen carrying out his duties wearing only a white coat. The instrument panel and the other meters and controls are situated outside the concrete shield which is his protection.

Checking activity levels

The possibility of contact with very small quantities of activity cannot be entirely precluded. This applies particularly to instrument trough areas in which contamination can occur during maintenance of instruments or the taking of samples. For this reason, areas of this type are separated from the main operating area by a barrier. Personnel entering these areas are required to change their shoes and wear special protective clothing. On leaving the area the shoes and clothing are left inside the barrier and are monitored for beta-gamma and alpha activity. If found to be active they are placed in special containers and removed from the plant for decontamination. The areas are also frequently monitored and any activity that arises is immediately removed. To ensure that activity has not been spread to operating areas regular checks are maintained both for surface contamination and to ensure that the level of activity in the atmosphere does not rise above background. On leaving the operational area the coverall and shoes are removed and washing of hands followed by beta-gamma and alpha monitoring is compulsory. The activity measurements are performed using an automatic machine which rings an alarm if the level of activity is above background. Should this occur, detailed monitoring is carried out by a member of the Health Physics Department who pinpoints the activity and supervises its removal by washing. Some indication of the standards which are set can be judged from the fact that the activity associated with the luminous dial of a watch is sufficient

to ring the alarm of the hand monitoring equipment. Periodic urine samples are also taken and analysed for fission-product and alpha content. This test is extremely sensitive and gives an indication of quantities of active material inhaled or ingested to the order of 10^{-12} gram.

In addition to the precautions taken against contamination, each individual entering the operational area is issued with a radiation film badge which measures exposure to gamma radiation. These films are checked at regular intervals and form an essential part of the general control. Also there are full-time medical officers and a well-equipped surgery, and examinations, blood counts and urine analyses are carried out as required.

The plant has operated under active conditions for about four years. In general, operation has been satisfactory and very good recovery efficiencies have been maintained. However, this period has not been entirely uneventful. The apparently simple act of charging active uranium rods to the dissolving unit presents quite a formidable problem when the rods contrive to block in the feed chute. This is a typical example of numerous incidents which would not arise in conventional non-active processes. Some difficulties have also been experienced due to the presence of certain impurities in the uranium rods. Although present to the extent of a few tens of parts per million, these tended to give rise to emulsification in the first extraction unit. This was overcome at the time by a modification to the initial flowsheet, but has subsequently been avoided by ensuring the removal of the impurity during the manufacture of the uranium rods. The problem of emulsification is of course one that is always present in solvent extraction processes and special precautions have to be taken that the solvent does not become associated with any reagents liable to increase this tendency.

Planned entry to medium cells

Probably one of the most serious difficulties has been the formation of sludges. Initially these tend to accumulate at solvent aqueous interfaces, but in time they are carried forward in the liquor stream and are deposited in pipes and the packing of the extraction units. This has given rise to complete blockages of pipes which have proved very difficult to free, especially as direct access to the pipes has been impossible because of the associated radiation. In the case of the extraction units such depositions impair the column performance and can give rise to flooding at normal flow rates. This difficulty has been overcome by periodic thorough washing of the pipes and columns with selected reagents. These sludges tend to act as absorbers of certain fission products and can give rise to local radiation levels many hundreds of times greater than the specific activity of the solution with which it is associated. In cases where the sludge adheres to pipes and vessels considerable difficulties are experienced in decontamination processes.

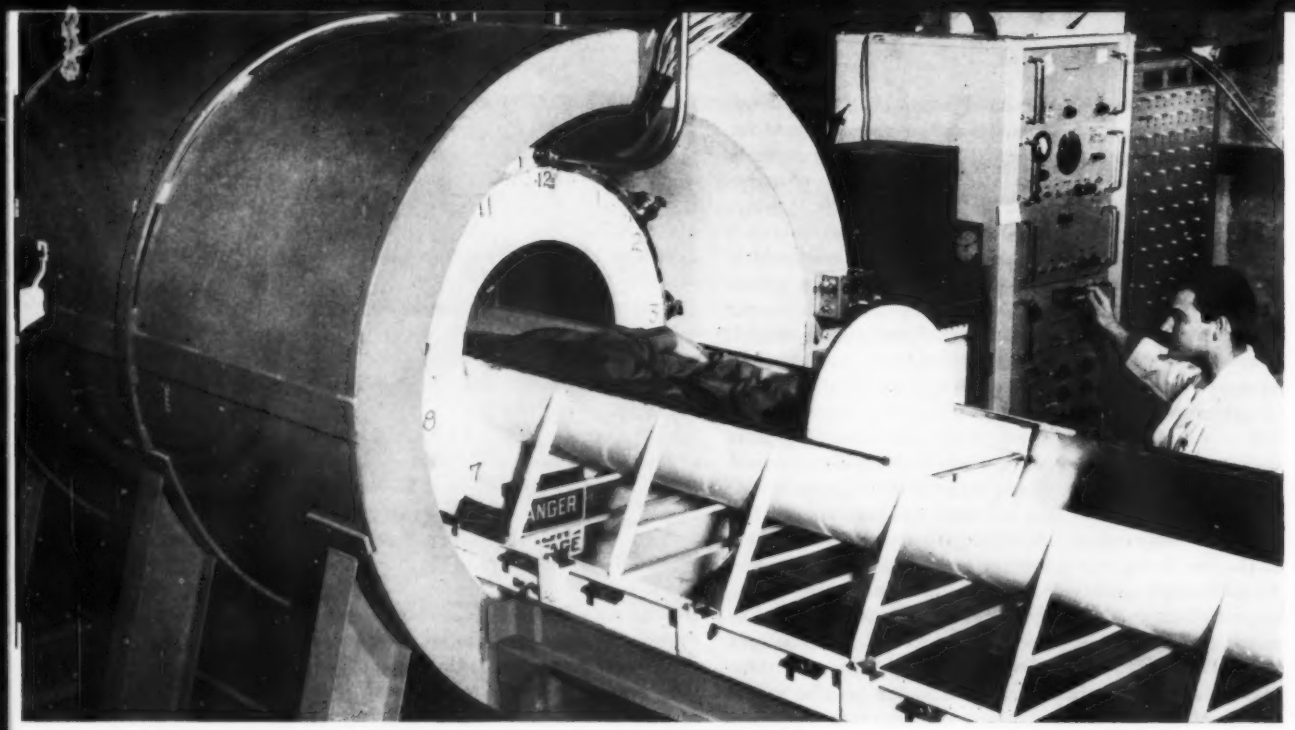
After operational experience had been gained it was realised that if access to the medium active cell could be made possible, a number of modifications to the plant could be done which would increase the throughput and improve efficiency and control. This, of course, implied passing through the shield into the cell where circumstances would be completely different because the plant would be unshielded. Preliminary surveys inside the cell were not encouraging since radiation levels of the order of many thousands of röntgens were measured. It was suspected that the radiation would be due in part to sludges which had settled out in vessels and to ion exchange between the solutions and some of the constituents of stainless steel. A programme of work was initiated which consisted in draining the plant and then washing it through repeatedly with selected reagents and water. Choice of reagent was limited because chemical attack on the stainless steel could not be tolerated.

After a trial period, this method of approach was found to be quite successful and radiation levels generally in the cell were reduced to the order of a röntgen, although individual vessels still showed radiation levels much above this. It is relatively easy to erect temporary shielding around such vessels and the important problem was to offer adequate protection to personnel. Ultimately a plastic pressurised suit was evolved which totally encloses the wearer and offers him an independent air supply. The suit weighs five pounds, the dome offers unrestricted visibility and a man may talk through it to his companions. In the unlikely event of the suit developing a small hole, because it is pressurised the flow of air is outwards and there is no danger of air from the cell entering the suit. Gradually "Planned Entry" to the cell was conceived. This consists in erecting a change area outside the entrance to the cell, at which point all personnel about to enter the cell put on a pressurised suit. They are told how long they are permitted to stay in the cell and work under constant supervision.

Using this method and special techniques, modifications have been carried out on plant which hitherto had been thought to be unmaintainable. One result has been a substantial increase in the throughput of the Windscale chemical plants, and work is now in hand which when completed will enable these plants to handle the output of ten reactors compared with the original two.

Considerable help was given to me by Mr T. G. Hughes in the preparation of this paper and I acknowledge my thanks to the Managing Director, UKAEA (IG) for permission to publish this work.

Fig. 8 ***Wearing a plastic pressurised suit, a worker emerges from an active area at the end of a predetermined safety period***



a NUCLEAR POWER correspondent reports on

Measuring body radioactivity

There are two basic methods of measuring the body burden of radioactive material of living subjects. The first is by excretion studies and depends on having data on the fractions excreted. The second is by an external radiation measurement and necessitates making assumptions about the location of the contaminant and the absorption of the radiation in the body. In recent years this second, more direct, method has attracted a great deal of attention, and the increasing numbers of nuclear reactors which are coming into operation throughout the world, leading to larger and larger segments of the population being potentially exposed, is giving it a new importance.

The extremely low value of the maximum permissible total body burden of many nuclides (1×10^{-7} curie for radium and 4×10^{-8} curie for plutonium) imposes a rather severe requirement on counter sensitivity, especially as it is really essential to make measurements below the tolerance level. Furthermore, it is also essential to make measurements of subjects who have not been exposed to radioactive contaminants and whose body burden is then largely resulting from the natural potassium content. This latter involves measurement down to 1×10^{-8} curie or less.

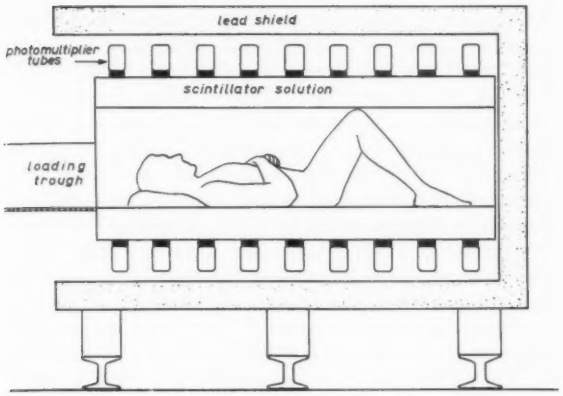
Several different approaches to the measurement of body radioactivity have been made. These range from the use of high-pressure ionisation chambers in association with valve or vibrating-reed electrometers to the use of scintillation counters in association with counting-rate meters or scalers. The first paper at the Conference was presented by Dr B. Hultqvist (Stockholm) and dealt with the design and use of the 4π counter designed by Professor Sievert using high-pressure ionisation chambers. Parallel papers were given by Mr J. Rundo dealing with the very similar system installed at the Finsen Hospital (Copenhagen), but designed and built at the Atomic Energy Research Establishment, Harwell, and by Dr P. F. J. Burch, who described the installation using high-pressure ionisation chambers installed at Leeds University. It is of interest to note that the Stockholm installation is in an underground cavern under about 50 metres of granite. There is also further local shielding provided by about 1 metre of water (in tanks) on all sides of the measuring chambers. With this system only the most penetrating of the cosmic radiation reaches the measuring chambers, and it is possible to use a complete ring of detectors, and the absorption effect (of the cosmic radiation by the person being monitored) is negligible. The position of the person within the measuring volume is also not critical. On the other hand, the two installations at Leeds and Copenhagen are surface installations, and it has been necessary to provide a system of chambers for measuring the radiation from the person plus background, and a cancelling system of chambers measuring the background only.

All these three installations have about equivalent sensitivities. Thus with the Finsen Hospital equipment it has proved feasible to measure 2×10^{-9} curie of radium (Ra^{226}) in equilibrium with its decay products with an accuracy of $\pm$ 20 per cent in a two-hour observation.

It is to be noted that the inability of the high-pressure ionisation chamber equipments to select events of a desired energy range results in a comparatively high background so that, as noted above, long counting times are required. It is for this reason that scintillation counter systems have attracted attention. Two approaches have been made. These are: (i) using liquid scintillators providing 4π geometry, and (ii) using sodium iodide scintillators

Fig. 1 (left) ***A subject enters the Los Alamos scintillation counter***

Fig. 2 (below) ***shows the tank containing 140 gal of terphenyl in toluene surrounded by 108 photomultiplier tubes***



Increasing radiation hazards demand new standards in counter sensitivity. Leeds conference hears of new instruments

in a simpler, but poorer, geometrical arrangement. At the Conference both these systems had their supporters. For example, Dr E. C. Anderson described the new 4π liquid scintillation counter which he and his colleagues have designed and installed at the Los Alamos Scientific Laboratory. It is shown schematically in Fig. 2, whilst a photograph of the complete installation is shown in Fig. 1. The scintillator is terphenyl in toluene and the tank holds about 140 gallons. The scintillations are detected with the aid of 108 photomultiplier tubes (DuMont 6292, 2 in. in diameter) inserted through the outer wall of the tank. The counter gives a much-improved performance over that possible with the ionisation-chamber system. Thus the counter has a background of about 400 counts per second and a counting efficiency of about 10 per cent for 1·5 MeV gamma rays. The natural potassium content of man (net count about 40 per second above background) can be measured with a precision of 5 per cent in 100 seconds of counting time. The ultimate sensitivity is about 5×10^{-10} curie.

Dr P. F. J. Burch also described the alternative system using liquid scintillators which is approaching completion at Leeds University. This uses five tanks of scintillating material, each approximately 6 in. by 6 in. and 10 in. long. These are to be arranged around the person to be monitored in a sitting position, one in front of his chest, three behind his back and one under his legs. For shielding purposes a steel housing is to be used 7 ft by 4 ft by 6 ft high, providing a total wall thickness of 6 in. of steel. Two photomultiplier tubes (EMI—6099, 5 in. in diameter) are to be used with each scintillator tank, the circuit arrangement being as shown in Fig. 3. According to Dr Burch the total background of the system should be about 150 counts

INCREASING numbers of nuclear reactors coming into operation throughout the world are leading to ever-increasing segments of the population being potentially exposed. Extremely low maximum permissible body burdens on many nuclides make counter sensitivity of the greatest importance. High pressure ionisation chambers and scintillation counters of several different kinds were described by speakers from Sweden, Denmark, the United States and Great Britain at a Conference held in Leeds in April 1956.

A CAUSE du nombre de plus en plus croissant de réacteurs nucléaires travaillant au monde entier, la possibilité d'être exposé au danger atteint des secteurs de plus en plus vastes de la population. La sensibilité des compteurs devient ainsi un facteur de la plus grande importance, vu l'exiguité extrême des charges maxima permissibles pour le corps humain en cas de nombreux nuclides. Des chambres d'ionisation à haute pression et des compteurs à scintillation de plusieurs types ont été charactérisés par des rapporteurs suédois, danois, américains et britanniques à l'occasion de la conférence de Leeds en avril 1956.

IMMER MEHR Kernreaktoren werden in der ganzen Welt inganggesetzt. Infolgedessen werden immer grössere Teile der Bevölkerung der dadurch verursachten potentiellen Gefahr ausgesetzt. Angesichts der äusserst niedrigen Werte der höchstzulässigen Körperbelastungen für viele Nuklide wird die Zählerempfindlichkeit zu einem äusserst wichtigen Faktor. Hochdruck-Ionisationskammern und Szintillationszähler einiger Typen wurden von Rednern aus Schweden, Dänemark, Vereinigten Staaten und Grossbritannien während der im April 1956 in Leeds abgehaltenen Konferenz beschrieben.

EL AUMENTO mundial en el número de reactores nucleares en operación resulta en que más secciones pobladas estén potencialmente expuestas. Debido a la reducida carga máxima permisible sobre muchos núcleos, la sensibilidad de los contadores asume la mayor importancia. Conferencistas de Suecia, Dinamarca, los Estados Unidos y la Gran Bretaña describieron varios tipos de cámaras de ionización a alta presión y contadores de centelleo, en una conferencia celebrada en Leeds en abril 1956.

ВСЛЕДСТВИЕ постоянного возрастания числа работающих ядерных реакторов в целом мире, все бо́льшие секторы населения подвергаются возможному риску облучения. Чувствительность счетчиков становится фактором громадного значения, так как максимальные допустимые нагрузки тела многими нуклидами чрезвычайно малы. Ионизационные камеры высокого давления и сцинтилляционные счетчики нескольких различных типов описываются докладчиками из Швеции, Дании, США и Великобритании как онференции, состоявшейся в Лидс в апреле 1956 г.

per second, and a normal subject (due to the natural potassium content) should give a counting rate on top of this background of about 20 counts per second.

The alternative scintillation counting system using thallium-activated sodium iodide as the scintillator is in use at the Argonne National Laboratory, U.S.A., and at the Atomic Energy Research Establishment, Harwell. Mr R. B. Owen and Dr Denis Taylor (Instrumentation Editor of NUCLEAR POWER) spoke about the AERE equipment at the meeting and gave details about their future plans.

The light output from a liquid scintillator under practical conditions is only $\frac{1}{6}$th to $\frac{1}{10}$th of that obtainable with thallium-activated sodium iodide. It is therefore much easier to obtain stable operation with a system using this latter phosphor. In addition, a sodium iodide scintillator provides a far better EHT characteristic. However, the main advantage of the inorganic phosphor is the enhanced response obtainable at low energies. From the figures reported at the meeting it appears that the sodium iodide scintillator can be used with good sensitivity down to about 10 KeV, whereas the liquid scintillator probably cannot be used below about 100 KeV gamma energy. This is obviously important when detecting the presence of pure beta-emittors by the emitted Bremstrahlung, or other substances by the x-rays emitted. On the other hand, sodium iodide scintillating material is expensive, and it would be difficult and very expensive to produce a 4π counter using this scintillator. The present AERE equipment uses four scintillation counters, each with sodium iodide crystals 2 in. long and $1\frac{3}{4}$ in. in diameter arranged on a centre line above the person being monitored, the spacing between the counters being 18 in. The shielding wall is of lead 2 in. thick.

Mr R. B. Owen at the meeting gave some details of the performance obtained with this equipment. In one series of experiments, for example, the mean background level with a polythene phantom (of a man) filled with tap-water was 1139·2 $\pm$ 1·4 counts per minute, and with 157 grams of potassium dissolved in 69 litres of water the additional counting rate was 108·3 counts per minute. Hence, assuming the background is known accurately, the body weight of potassium can be determined with an accuracy of $\pm$ 10 per cent in about 10 minutes of counting time. The reduced sensitivity as compared with the liquid systems is due to the poorer geometry.

An estimate was also made at the meeting of the sensitivity obtainable with pure beta-emitters. For example, P^{32} gives approximately 0·05 photons of energy greater than 50 KeV per beta-particle. Thus the standard deviation which would be obtained in a 10-minute count would correspond to 30×10^{-9} curies of P^{32} with this present equipment. The detectability of Sr^{89} and $Sr^{90} + Y^{90}$ should also be comparable with this.

Mr R. B. Owen explained towards the end of his contribution that the present AERE equipment was being rebuilt using four EMI photomultipliers type 6099, each employing a sodium iodide scintillator $4\frac{1}{2}$ in. in diameter and 2 in. thick, and that this with a normal man should allow an accuracy of measurement of K body burden of $\pm$ 3 per cent in a 10-minute count and of $\pm$ 1 per cent in a 90-minute count.

At the close of the session on body monitoring it was noted that it was now regarded as important to provide equipment which allowed the identification and measurement of specific nuclides in the presence of the natural potassium activity. This can be provided only by using a scintillation counter system, and the sodium iodide scintillator appears to offer very definite advantages in this respect. For example, Am^{241} can with energy discrimination be identified and measured by the 59 KeV gamma rays accompanying 40 per cent of the disintegrations (with a liquid scintillator these energies would be lost in the photocell noise). A body burden of 6×10^{-8} curie of Am^{241} should be easily distinguished on top of $1{\cdot}2 \times 10^{-8}$ curies of natural K^{40} activity, and this has been confirmed by actual measurement by Mr Rundo (AERE).

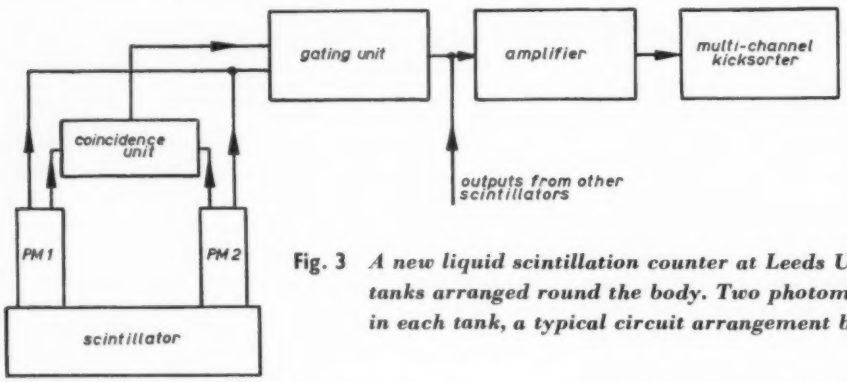


Fig. 3 *A new liquid scintillation counter at Leeds University uses five separate tanks arranged round the body. Two photomultiplier tubes are used in each tank, a typical circuit arrangement being as shown*

The situation with Pu^{239} is less favourable. It is instructive to consider the possibilities. Detection of a body burden of 4×10^{-8} curies soluble plutonium would have to be done through the 17 KeV L x-rays. The gamma-rays from radium in the skeleton are attenuated by an equivalent of 5 cm of tissue. If it is assumed that the Pu^{239} will distribute itself in the same way, then 2 per cent of the L x-rays will emerge from the 5 cm of tissue. Thus, in this case, it is necessary to detect $4 \times 10^{-8} \times 4 \times 10^{-2} \times 2 \times 10^{-2} = 3{\cdot}2 \times 10^{-11}$ curie. However, it is possible to use a kicksorter with a channel width of, say, $\pm$ 8 KeV and collect 95 per cent of the counts due to the sample, and at the same time reduce the background counts by about 50 times. It is also possible to gain some advantage by using a thinner crystal. Taking account of all these factors, it would seem that detecting the mpl of Pu^{239} (4×10^{-8} curie) as body burden should be achievable in 5 minutes of counting time.

Figs. 1 and 2 are by courtesy of Dr E. C. Anderson.

*4·2 × 10⁻² quanta of 17 KeV x-rays are emitted per alpha-particle from Pu^{239}

Reactor Physics — 2

by James F. Hill Senior Lecturer, Reactor School, Harwell

1. Thermal neutrons

In the previous article it was shown that one important type of neutron in a reactor was the thermal neutron. By this was meant a neutron in thermal equilibrium with the atoms or molecules with which it is colliding. These neutrons, on average, do not lose any energy on collision.

Now if we have a large number of neutrons in thermal equilibrium with matter they will not all have the same velocity, but a distribution of velocities. This is exactly analogous to the case of molecules of a gas in thermal equilibrium and we assume that, in fact, the distribution of neutron velocities is the same as that of gas molecules, namely the Maxwell-Boltzmann distribution, where

$$\frac{dn}{n} = \frac{4}{\sqrt{\pi}} \frac{v^2}{v_0^3} e^{-v^2/v_0^2} dv \qquad (2.1)$$

Here, dn is the number of neutrons per unit volume with velocities in the velocity range v, $v + dv$ and n is the total number of neutrons per unit volume in the system. Equally well, dn and n may refer to any volume in the system.

The shape of the distribution is as shown in Fig. 2.1.

It can be seen that v_0 is the most probable velocity; that it is the velocity corresponding to the maximum number of neutrons.

It is also a property that v_0 can be related to the absolute temperature T by the equation

$$\tfrac{1}{2}mv_0^2 = kT \qquad (2.2)$$

where m is the mass of the neutron ($1{\cdot}6747 \times 10^{-24}$ gm) and k is Boltzmann's constant ($1{\cdot}38042 \times 10^{-16}$ erg per degree). Thus an absolute temperature may be related to the neutron velocity from (2.2) by

$$v_0 = 1{\cdot}2840 \times 10^4 \sqrt{T} \text{ cm/s} \qquad (2.3)$$

Thus, for a temperature of 20°C (293·16° absolute), $v_0 = 2198$ m/s. This is usually simply taken as 2200 m/s.

Also, $\frac{1}{2}mv_0^2$ is the kinetic energy E of the neutron at the most probable velocity* and so

$$E = kT = 8{\cdot}630 \times 10^{-5}\ T \text{ eV} \qquad (2.4)$$

and again for $T = 20$°C, E is 0·0253 eV. Thus an energy of 0·0253 eV is spoken of as thermal energy. This is usually simply taken as 0·025 eV.

It is customary, then, to characterise thermal neutrons at room temperature (20°C) by a velocity of 2200 m/s, and an energy of 0·025 eV. However, it is to be remembered that this refers only to the neutrons at the maximum of the distribution against velocity. If we are concerned with a property relating to the average thermal neutron the average velocity $\bar{v}$ of the neutron must be used, and it can be shown from (2.1) that

$$\bar{v} = 2v_0/\sqrt{\pi} = 1{\cdot}128v_0 \qquad (2.5)$$

* It should be noted that E is not the most probable energy. If (2.1) is put in terms of E and not v it will be seen that the most probable energy is given by $E_0 = \frac{1}{2}E = \frac{1}{2}kT$.

2. Neutron cross-section

We have shown above how thermal neutrons can be characterised by one velocity and in what follows it will always be assumed that we can deal with neutrons of one velocity only. In the Part I of this series, the neutron cross-section was discussed qualitatively: we shall now give the term a precise definition.

Consider a uniform beam of neutrons, all of the same velocity v, with n neutrons per cm³ in the beam. Let the beam strike an infinitesimally thin layer of atoms of a material in a perpendicular direction. Also, let the number of atoms per cm³ of the material be N; the area of the material, A; and the thickness of the layer, X. Then the number of interactions, I, of a particular type between the neutrons and the nuclei is given by

$$I = \sigma(v)nvNA\delta x \qquad (2.6)$$

where the quantity $\sigma(v)$, a function of the velocity of the neutrons, is called the cross-section for the particular interaction.

It is seen from (2.6) that σ (it is not customary to indicate the dependence of σ on v) has the dimension of area.

The product of n and v is called the neutron flux,

$$\phi = nv \qquad (2.7)$$

and ϕ will be measured in neutrons per cm² per sec. For a beam of neutrons, ϕ represents the number of neutrons crossing a square centimetre per second. It will be seen later that this interpretation of the flux is not generally true.

The quantity $N\sigma$ is called the macroscopic cross-section and is the cross-section of one cubic centimetre of the material. It is written Σ, so that

$$\Sigma = N\sigma \qquad (2.8)$$

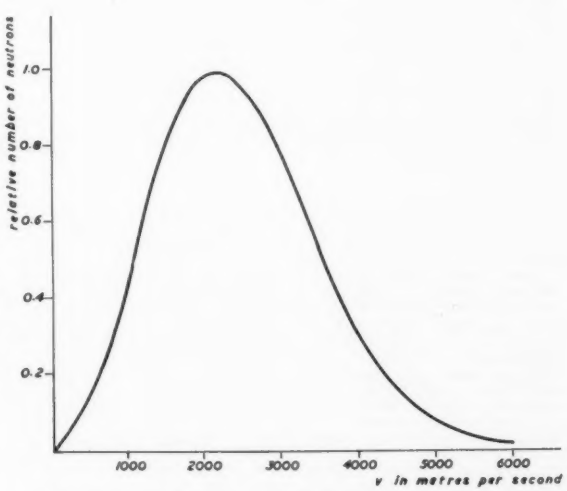


Fig. 2.1 *The Maxwell-Boltzmann distribution*

THE BEHAVIOUR of thermal neutrons is discussed by first demonstrating that they obey the Maxwell distribution of velocities, and the important properties of this distribution are given.

It is then shown that thermal neutrons can be assumed to have a constant velocity. From this assumption, their behaviour in contact with matter can be studied. This is done by first defining a neutron cross-section. Then the consequence of this on the attenuation of a beam of neutrons penetrating matter is found. This result is then used to calculate the neutron current, which is the net number of neutrons crossing unit area in unit time. Finally, the neutron diffusion equation is derived. This equation describes the variation of the neutron flux (neutron density multiplied by velocity) in a system as a function of the space co-ordinates and of the time.

L'AUTEUR étudie la nature des neutrons thermiques en prouvant d'abord qu'ils obéissent la distribution Maxwell des vélocités et en démontrant les propriétés importantes de cette distribution.

On montre ensuite qu'il est possible d'attribuer aux neutrons thermiques une vélocité constante. Cette supposition permet d'étudier les propriétés de ces neutrons en contact avec la matière. A cet effet on définit d'abord la section efficace des neutrons. Ensuite on en trouve l'influence sur l'atténuation d'un faisceau des neutrons pénétrant la matiére. Ce résultat est employé pour calculer le courant de neutrons, c'est-à-dire le nombre net des neutrons traversant l'unité de surface en unité de temps. Finalement on obtient l'équation de diffusion pour les neutrons. Cette équation décrit la variation du flux de neutrons (densité de neutrons multipliée par vélocité) dans un système comme une fonction des coordonnées spatiales et de temps.

DAS VERHALTEN von Wärmeneutronen wird erörtert, indem zuerst gezeigt wird, dass dieselben die Maxwellsche Geschwindigkeitsverteilung befolgen; wichtige Eigenschaften dieser Verteilung werden angeführt.

Es wird demnächst gezeigt, dass man annehmen kann, dass Wärmeneutronen eine konstante Geschwindigkeit haben. Auf dieser Annahme basierend, kann man das Verhalten der Wärmeneutronen im Kontakt mit Materie untersuchen. Zu diesem Zwecke definiert man vorerst den Neutronenquerschnitt. Dann findet man die Auswirkung dieser Definition auf die Schwächung eines in die Materie eindringenden Neutronenbündels. Dieses Resultat wird demnächst zur Ausrechnung des Neutronenstromes (Nettozahl von Neutronen, welche durch Flächeeinheit pro Zeiteinheit hindurchgehen) benutzt. Zum Schluss wird die Neutronendiffusionsgleichung abgeleitet. Diese Gleichung schildert die Veränderung des Neutronenflusses (Neutronendichte mal Geschwindigkeit) in einem System als Funktion der Raumkoordinaten und der Zeit.

EL COMPORTAMIENTO de los neutrones termales es tratado demostrando primeramente que obedecen a la distribución de velocidades Maxwell, y se detallan las caracteristicas esenciales de esta distribución.

Seguidamente se demuestra que se puede asumir que los neutrones termales tienen una velocidad constante. Establecida esta suposición, puede estudiarse su comportamiento en contacto con sustancias, primeramente determinando una sección transversal de neutrones. Entonces se acierta su efecto sobre la atenuación de un rayo de neutrones al penetrar sustancias. Este resultado es utilizado para calcular la corriente neutrónica, la cual es el número neto de neutrones que atraviezan unidad de area en unidad de tiempo. Finalmente, se deduce la ecuación de difusión de los neutrones. Esta ecuación define la variación del flujo de neutrones (la densidad neutrónica multiplicada por la velocidad) en un sistema, como una función de los coordenados de espacio y del tiempo.

ОБСУЖДАЯ поведение тепловых нейтронов, автор сначала доказывает, что эти нейтроны подчиняются максвелловскому распределению скоростей, и приводит важные свойства этого распределения.

Затем указывается на возможноеть предположения, что тепловые нейтроны имеют постоянную скорость. Это предположение позволяет исследовать поведение нейтронов в соприкосновении с материей. Для этого сначала дается определение эффективного сечения для нейтронов. Потом обнаруживается влияние этого определения на ослабление пучка нейтронов, проникающего внутрь материи. Этот результат используется для расчета тока нейтроноь, равного чистому числу нейтронов, проходящих через единицу площади в единицу времени. Наконец выводится уравнение диффузии нейтронов, изображающее изменение потока нейтронов (плотность нейтронов, умноженная на скорость) в данной системе, как функцию пространственных координат и времени.

and has dimensions of inverse length (cm^{-1})

Then (2.6) becomes

$$I = \phi \Sigma V \tag{2.9}$$

where $V = A\delta x$ is the volume of material presented to the neutron beam.

3. Neutron attenuation in a foil

We now wish to consider the problem of a beam of neutrons striking a foil of material. It is assumed in this instant that the material only captures neutrons and then does not have a large capture cross-section. The problem, then, is to find how many of the neutrons striking the foil penetrate to any given distance inside the foil. (It is necessary to assume that the foil does not have a large cross-section, otherwise the simple argument presented here would not hold. This is because, if the cross-section were large, nuclei inside the foil would be, in effect, screened from the neutrons by those near the face on which the neutrons are falling.)

We then have the situation shown in Fig. 2.2, where the foil is of thickness x.

Consider an element δx at distance x inside the foil. Let ϕ be the neutron flux at x and $\phi + \delta\phi$ the flux at $x + \delta x$. It follows from (2.9) that the number of neutrons captured in δx per cm^2 of foil per second is

$$\phi \Sigma_c \delta x \tag{2.10}$$

where Σ_c is the macroscopic capture cross-section.

Now $\phi + \delta\phi$ is the number per second of neutrons per cm^2 passing $x + \delta x$ and ϕ the similar number passing x, so that $\phi - (\phi + \delta\phi)$ must be the number per second captured in δx, and so using (2.10)

$$-\delta\phi = \phi \Sigma_c \delta x \tag{2.11}$$

So $\delta\phi$ must be negative, as $\phi\Sigma_c\delta x$ is positive. This simply means that the flux decreases in going from x to $x + \delta x$.

Then, in the limit, from (2.11)

$$\frac{d\phi}{dx} = -\Sigma_c \phi \tag{2.12}$$

$$\text{or } \phi(x) = \phi(O) e^{-\Sigma_c x} \tag{2.13}$$

where $\phi(x)$ is the flux at distance x and $\phi(O)$ is the flux on the face of the foil, that is, the flux in the neutron beam.

Thus the fraction of neutrons passing through the foil is $\phi(x)/\phi(O) = e^{-\Sigma_c}$.

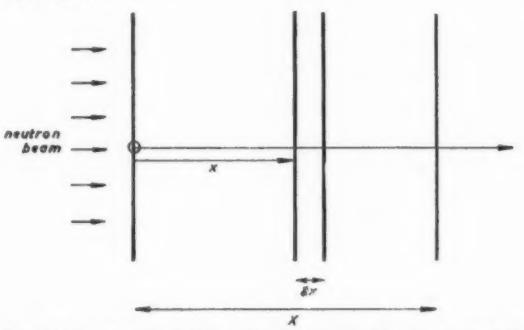


Fig. 2.2 *Attenuation of a neutron beam in a foil*

This argument can be repeated, supposing that the foil only scattered neutrons. In this case, however, the interpretation of the result is slightly different. We should find,

$$\phi(x) = \phi(O) e^{-\Sigma_s x} \tag{2.14}$$

but $\phi(x)$ now has to be interpreted as the flux of neutrons

which have not made a scattering collision before reaching the position x.

In general,

$$\phi(x) = \phi(O)e^{-\Sigma_T x} \tag{2.15}$$

where Σ_T is the total macroscopic cross-section. Then $\phi(x)$ in (2.15) represents the flux of neutrons reaching the position x without making a collision of any sort, whether it be capture, fission, scatter or any other process.

4. Mean free path

Suppose we now return to (2.13) and calculate from this the average distance a neutron travels before being captured in an infinitely thick foil. The chance that a neutron is captured at distance x is given by (2.10) as $\phi\Sigma_c\delta x$ and so the average distance travelled before capture, which we call λ_c, is given by

$$\lambda_c = \frac{\int_0^\infty x \,.\, \phi\Sigma_c \,.\, dx}{\int_0^\infty \phi\Sigma_c \,.\, dx} \tag{2.16}$$

which, substituting for ϕ from (2.12), gives

$$\lambda_c = \frac{1}{\Sigma_c} \tag{2.17}$$

λ_c is thus seen to have dimensions of length (cm), as indeed it should, and it is called the capture mean free path.

Again, this argument can be applied to any process with the general result that

$$\lambda = \frac{1}{\Sigma} \tag{2.18}$$

where the process may be fission, absorption, scatter, etc.

Finally, a total mean free path λ_T is defined by

$$\frac{1}{\lambda_T} = \frac{1}{\lambda_c} + \frac{1}{\lambda_f} + \frac{1}{\lambda_s} + \ldots \tag{2.19}$$

as a consequence of the definition

$$\sigma_T = \sigma_c + \sigma_f + \sigma_s + \ldots \tag{2.20}$$

for the total cross-section.

λ_T thus represents the average distance a neutron travels between collisions of any type.

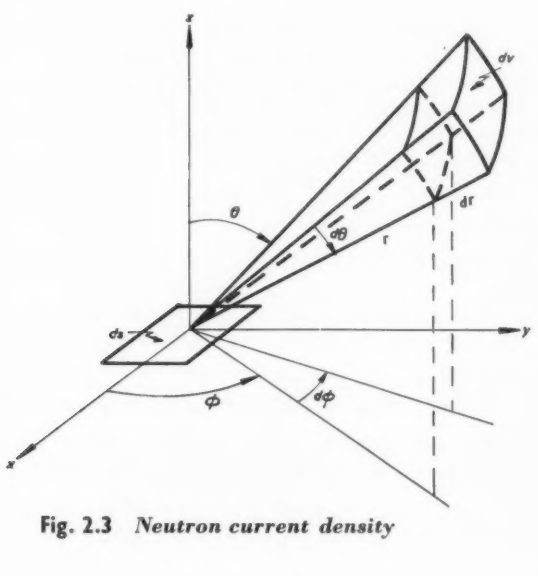


Fig. 2.3 *Neutron current density*

5. Fundamental equations governing the behaviour of thermal neutrons

We have already seen how the behaviour of thermal neutrons can be likened to that of the molecules of a gas. This analogy will now be carried further in order to obtain the fundamental equations governing what we shall therefore call *the diffusion of neutrons.*

In deriving these equations, four simplifying assumptions are made. These are:

(1) The neutrons all have the same velocity.

(2) Absorption in the medium can be neglected compared to scattering. (In graphite, for example, $\sigma_s/\sigma_c \simeq 1000$.)

(3) The scattering of the neutrons is isotropic in the laboratory system of coordinates.

This means simply that if we reduce the velocity of the nucleus to zero, the colliding neutron is equally likely to be scattered by the nucleus in any direction. (We shall, in fact, show how to correct for the fact that this assumption is not a good one.)

(4) The neutron density at any point can be expressed as a Taylor expansion about the origin of coordinates, correct to second-order terms.

The physical interpretation of this condition is that the neutron density is approximately a quadratic curve over distances of the order of a few mean free paths.

Using these assumptions we are now in a position to calculate the number of neutrons crossing an area dS (see Fig. 2.3) situated at the origin of coordinates, and thence to find the number crossing one cm² at the origin. We shall assume there is no variation of the neutron density with time.

If n is the steady state neutron density at any point P whose coordinates are (x, y, z) then the number of neutrons scattered out of the volume element dV surrounding P is, using (2.9)

$$nv\Sigma_s dV \tag{2.21}$$

where v is the (constant) neutron velocity.

Using assumption (3), the chance that a neutron is scattered from dV in such a direction that it passes through dS is

$$\frac{\cos\theta \, dS}{4\pi r^2} \tag{2.22}$$

From (2.15), the chance that a neutron leaving dV reaches the origin without making a collision of any sort, is

$$e^{-\Sigma_T r},$$

but we use assumption (2) here, and say this is approximately

$$e^{-\Sigma_s r} \tag{2.23}$$

which then represents the chance that a neutron from dV reaches dS without making a further collision.

Thus the number of neutrons per sec. making a collision in dV and reaching dS without further collision is the product of (2.21), (2.22) and (2.23). Then the total number of neutrons passing through dS from above the x, y plane is obtained by integrating this product over the region. The resultant quantity is written as $J_z{-}dS$, so

$$J_z{-}dS = \frac{\Sigma_s v dS}{4\pi}\int_0^\infty\int_0^{2\pi}\int_0^{\pi/2} ne^{-\Sigma_s r}\cos\theta\sin\theta\,d\theta\,d\phi\,dr \tag{2.24}$$

as $dV = r^2 \sin\theta \, d\theta \, d\phi \, dr$.

The quantity J_{z-} is called the neutron current density in the negative z-direction.

Assumption (4) enables n, which is a function of x, y and z, to be written as

$$n(x, y, z) = n(0) + x\left(\frac{\partial n}{\partial x}\right)_0 + y\left(\frac{\partial n}{\partial y}\right)_0 + z\left(\frac{\partial n}{\partial z}\right)_0 \tag{2.25}$$

where the derivatives are taken at the origin, and $n(0)$ represents the value of n at the origin. The second-order terms have been omitted as they are zero or cancel out in deriving the difference in (2.28).

This, substituted into (2.24), yields

$$J_{z-} = \frac{nv}{4} + \frac{v}{6\Sigma_s}\left(\frac{\partial n}{\partial z}\right)_0 \tag{2.26}$$

Similarly, the neutron current density in the positive z-direction J_{z+} can be shown to be

$$J_{z+} = \frac{nv}{4} - \frac{v}{6\Sigma_s}\left(\frac{\partial n}{\partial z}\right)_0 \tag{2.27}$$

The difference between J_{z+} and J_{z-}, given the symbol J_z, is called the net neutron current density, usually abbreviated to neutron current.

$$J_z = J_{z+} - J_{z-} = -\frac{v}{3\Sigma_s}\left(\frac{\partial n}{\partial z}\right)_0 \tag{2.28}$$

J_z then represents the net number of neutrons crossing one cm² of plane surface per sec. Its dimensions are, therefore, neutrons per cm² per sec.

Using (2.18), (2.28) can be written as

$$J_z = -\frac{1}{3} v\lambda_s \left(\frac{\partial n}{\partial z}\right)_0 \tag{2.29}$$

By an exactly similar argument, treating the x and y directions separately,

$$J_x = -\frac{1}{3} v\lambda_s \left(\frac{\partial n}{\partial x}\right)_0 \tag{2.30}$$

and

$$J_y = -\frac{1}{3} v\lambda_s \left(\frac{\partial n}{\partial y}\right)_0 \tag{2.31}$$

These results will hold good so long as the assumptions made in deriving them hold. However, assumption (4) will not be valid in regions where the neutron density changes rapidly. This will happen, for example, near strong sources of neutrons, near the boundary between two media having different diffusing properties or at the outside boundary of a medium.

The restrictions imposed by assumption (3) can be partially removed by a correction to (2.29)...(2.31). This correction is derived by considering a more accurate formulation of the problem of neutron diffusion called transport theory which does not require the restriction of assumption (3).

The corrected version of (2.24) is

$$J_z = -\frac{1}{3} v \frac{\lambda s}{1 - \bar{\mu}} \left(\frac{\partial n}{\partial z}\right)_0 \tag{2.32}$$

and similarly for J_x and J_y. The quantity $\bar{\mu}$ is the average cosine of the angle of scattering of the neutron in the laboratory system of coordinates. Its value, which will be found later when the subject of neutron collisions is discussed, is $2/3A$, where A is the mass number of the scattering nucleus.

It is customary to write

$$\lambda_t = \frac{\lambda_s}{1 - \bar{\mu}} \tag{2.33}$$

and call λ_t the transport mean free path. This also implies a transport cross-section defined by

$$\sigma_t = \sigma_s (1 - \bar{\mu}) \tag{2.34}$$

Using (2.33), (2.32) may be written

$$J_z = -\frac{1}{3} v\lambda_t \frac{\partial n}{\partial z}$$

or

$$J_z = -D\frac{\partial n}{\partial z} \tag{2.35}$$

where

$$D = \frac{1}{3} v\lambda_t \tag{2.36}$$

is called the diffusion coefficient. It has dimensions of cm² per sec.

This result for the neutron current can now be used to calculate the net loss of neutrons from any volume of the diffusing medium.

Consider a rectangular volume element dV located at the point (x, y, z) as shown in Fig. 2.4.

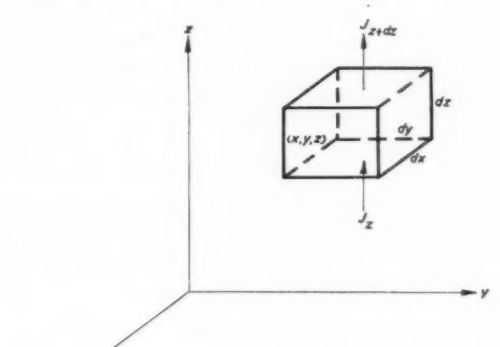


Fig. 2.4 *Neutron leakage*

Then the net number of neutrons passing into dV through the face parallel to the x, y plane through the point (x, y, z) is J_z dxdy per sec. Similarly, the net number passing out through the opposite face is J_{z+dz} dxdy per sec. So the net outflow per sec. from dV in the z-direction is the difference between these quantities, that is,

$$(J_{z+dz} - J_z)\,\mathrm{dxdy} \tag{2.37}$$

and this, using (2.35), becomes

$$\begin{aligned} &-D\left[\left(\frac{\partial n}{\partial z}\right)_{z+dz} - \left(\frac{\partial n}{\partial z}\right)_z\right]\mathrm{dxdy} \\ &= -D\frac{\partial^2 n}{\partial z^2}\,.\,\mathrm{dxdydz} \\ &= -D\frac{\partial^2 n}{\partial z^2}\,.\,\mathrm{d}V \end{aligned} \tag{2.38}$$

Similar results hold for the x — and y — directions and so the total neutron loss from unit volume per sec. is

$$-D\left[\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} + \frac{\partial^2 n}{\partial z^2}\right]$$

which is written

$$-D\nabla^2 n \tag{2.39}$$

where for rectangular coordinates

$$\nabla^2 \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \tag{2.40}$$

The operator ∇^2 can also be evaluated for other other coordinate systems. In particular:

Spherical coordinates

$$\nabla^2 \equiv \frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial}{\partial \theta}\right) + \frac{1}{r^2 \sin^2\theta} \cdot \frac{\partial^2}{\partial \phi^2}$$

and in the particular case of spherical symmetry, that is, no dependence on θ and ϕ

$$\nabla^2 \equiv \frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} \tag{2.41}$$

Cylindrical coordinates

$$\nabla^2 \equiv \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}$$

and in the case where there is symmetry about the axis of the cylinder

$$\nabla^2 \equiv \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2} \tag{2.42}$$

6. The diffusion equation

We are now in a position to derive an equation which will give the rate of change of neutron density (or flux, as they are here proportional due to the assumption of constant neutron velocity) as a function of the space coordinates of the medium in which the neutrons are diffusing.

To do this, we consider unit volume of the medium. Then the rate of change of neutron density will be given by the difference between the rate at which neutrons are produced in the volume and the rate at which they are removed from the volume. Now neutrons are removed from the volume by diffusion loss, which will be called neutron leakage, as given by (2.40) above and also by neutron capture.

We can now write the fundamental equation:

Rate of change of neutron density
= rate of production of neutrons per unit volume
− rate of leakage of neutrons per unit volume
− rate of absorption of neutrons per unit volume (2.43)

Then if S is the rate of production of neutrons per unit volume, using (2.40) and (2.9), (2.43) becomes

$$\frac{\partial n}{\partial t} = S + D\nabla^2 n - \Sigma_a n v \tag{2.44}$$

and this is the time dependent diffusion equation.

In the steady state $\partial n/\partial t = 0$, so

$$S + D\nabla^2 n - \Sigma_a n v = 0 \tag{2.45}$$

and in regions where a neutron source is not present

$$D\nabla^2 n - \Sigma_a n v = 0 \tag{2.46}$$

Using (2.36) this may be written as

$$\nabla^2 n - \frac{3}{\lambda_a \lambda_t} n = 0$$

which we write as

$$\nabla^2 n - \frac{n}{L^2} = 0 \tag{2.47}$$

where

$$L^2 = \frac{1}{3}\lambda_a \lambda_t \tag{2.48}$$

The physical significance of L, which is called the diffusion length, will be seen later.

It is often convenient to put $L^{-1} = \mathrm{K}$, and so (2.47) is then

$$\left.\begin{aligned} \nabla^2 n - \kappa^2 n &= 0 \\ \text{or equally} \quad \nabla^2 \phi - \kappa^2 \phi &= 0 \end{aligned}\right\} \tag{2.49}$$

Thus in those parts of a diffusing medium which do not contain a neutron source, the distributions of neutron density and flux are given respectively by (2.48) and (2.49). If the neutron distribution is maintained by localised sources of neutrons, then the method of solution is to solve the source independent equation and then insert the effect of the source by means of a condition on the solution. How this is done will be demonstrated in the next article in this series, which will deal with the solution of the diffusion equations.

Notation

- A area
- D diffusion coefficient—$\frac{1}{3}\lambda_t v$
- E thermal neutron energy—kT in a Maxwellian spectrum
- E_0 most probable energy in a Maxwellian spectrum—$\frac{1}{2}kT$,
- I number of neutron interactions per second
- J_+ neutron current density in positive direction
- J_- neutron current density in negative direction
- J neutron current $J_+ - J_-$
- k Boltzmann's constant—$1{\cdot}38042 \times 10^{-16}$ erg/°C
- L diffusion length—$\frac{1}{3}\lambda_a \lambda_t$,
- m mass of neutron—$1{\cdot}6747 \times 10^{-24}$ gm
- N number of atoms per cm³
- n neutron density
- S source strength—number of neutrons produced per cm³ per sec by a source
- T absolute temperature
- v neutron velocity
- v_0 most probable velocity in a Maxwellian spectrum—$1{\cdot}284 \times 10^4\ T$ cm
- $\bar{\ }$ average velocity in a Maxwellian spectrum—$1{\cdot}128 v_0$
- V volume

- κ inverse diffusion length—L^{-1}
- λ mean free path
- $\bar{\mu}$ average cosine of angle of scatter in laboratory system
- σ cross-section
- Σ macroscopic cross-section—$N\sigma$
- ϕ neutron flux—nv

Subscripts

- c represents neutron capture
- s represents neutron scattering
- t represents neutron transport
- T represents total

EQUIPMENT

Thin window feature of new Mullard GM tube

Two new geiger-müller tubes have recently been announced by Mullard Ltd, Century House, Shaftesbury Avenue, London WC2—a mica end-window type and a liquid-sample tube. These are claimed to have a life of at least 10^9 counts and since they are designed for standardised working voltages, any tube of a type is a direct plug-in replacement for any other—a factor of importance in cases where a number of tubes are in use.

The mica end-window tube—type MX/23—has an extremely thin mica closure, the thickness being between 1·5 and 2·5 mg/cm² (·0002 in.—·00035 in.) which makes it suitable for measuring very low energy radiation and it should be particularly useful with carbon 14—an isotope widely used in tracer techniques. Another feature is the low level of background count, which has been achieved by the use of materials with a minimum radioactive content. In conventional lead castles, background counts are as low as ten a minute.

The liquid-sample tube—type MX/124—is of conventional design and is fitted with a ground-glass stopper. This makes it suitable for a volatile liquid and it also facilitates decontamination after use, since solutions in the tube can be shaken. The extension piece to a lead castle, necessary when a stopper is used, is already in production by another manufacturer. This tube is also available without the stopper—type MX 124/01.

One of two new Mullard geiger-müller tubes, the type MX/124 is designed for liquid samples. It is also available without the ground-glass stopper

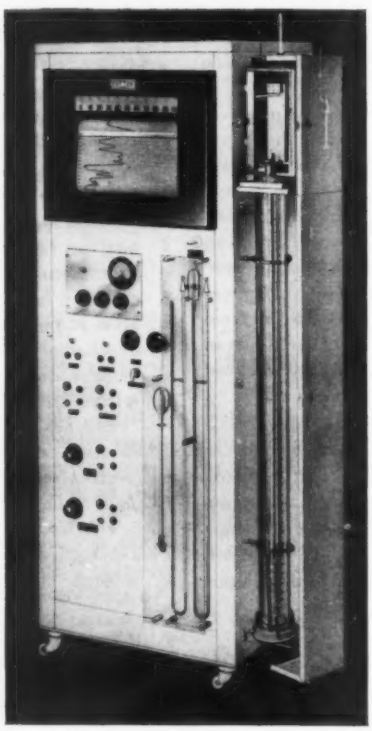
Vapour phase chromatography accuracy equals mass spectrometer

A newly-developed apparatus for the analysis of mixtures of liquids of low to medium molecular weight vaporising between 20° and 200°C at atmospheric pressure is available from Griffin & George Ltd, Alperton, Middlesex. With close control it is claimed to give repeatable quantitative results with an accuracy equal to that of the mass spectrometer. Analyses of gaseous mixtures may also be carried out.

The analysis of organic chemicals in industry presents an ever-increasing problem to chemists responsible for control of quality and for analytical research in connection with new processes and products. The mass spectrometer is a powerful instrument, though the computational time required for complex mixtures may narrow the gap between it and other methods.

Fractional distillation has been very widely employed, and well-designed columns with efficient packings can achieve distillation efficiencies of 200 theoretical plates. Overlap fractions, one of the chief disadvantages, can be partly overcome by the addition to the mixture of a carrier liquid, so that one component is selectively removed in the distillate.

A new method of analysis—vapour phase partition chromatography (V.P.C.)—was announced in 1952 by the Nobel Prize Winner, Dr A. J. P. Martin, FRS, and his colleague Dr A. T. James; this has been developed almost exclusively by British chemists and is now used extensively in the laboratories of many organisations, both industrial and educational. For many purposes, because of its technical advantages, the V.P.C. method has replaced the mass spectrometer.



The Griffin and George V.P.C. apparatus speeds analysis, provides chart recording

By the new method it is easily possible to achieve efficiencies equal to 2000 theoretical plates in columns only 4 ft long and the hours required for conventional distillation are reduced to minutes. Whilst the technique has many similarities to distillation, it is closely allied to chromatography, wherein substances are separated by distribution between stationary solid and moving liquid phases.

When a small drop of a liquid mixture is injected into the V.P.C. apparatus, it is vaporised and the vapour is swept by a gas, usually nitrogen, through a column filled with a suitable packing. This packing separates the individual components from one another, so that each component is swept out of the column at a particular time. The rates of elution of the different constituents are determined by their relative partitions between the gas and the liquid phases, the more volatile constituents travelling more rapidly than the less volatile. With correct conditions of operation each component leaves the column, separated from all other constituents, without any overlap fractions, and affects the electrical resistance of a hot wire. The changes in e.m.f. thus produced are recorded as peaks on the moving chart of a recorder.

The position of each peak reveals the identity of each component, and from the height of each peak the amount present can be determined. By this means, small samples can be analysed for as many as a dozen components in 15–60 minutes. The method has been applied to many different kinds of organic chemicals, and works equally well with small volumes of gas mixtures.

Craig liquid/liquid apparatus now with 200 tubes

Shown at the BIF, on the stand of Quickfit & Quartz Ltd, Stone, Staffs, was a 200-tube Craig counter-current liquid/liquid extraction machine used for the separation of dilute solutions of complex materials. One of these was recently exported to Norway.

The principle is basically the same as that of partition chromatography, but the Craig method (*Analytical Chemistry*, 1950, 22, 1346; 1951, 23, 41) gives a product on a 20–30 g scale instead of a 20–30 mg scale as in chromatography. The theoretical principles underlying both methods are the same, *i.e.* partition of the solute between two immiscible solvents.

The "Quickfit" machine uses compact all-glass tubes of 25-ml operating capacity. Nominally, the volumes are made such that they do not vary by more than 5 per cent, although in practice the variation is usually much lower. It has been found that a variation of this order does not affect the results when graphically expressed.

Each tube is separate and interchangeable. Thus the glassware may readily be dismantled and cleaned, and breakage replacement costs are reduced to a minimum. It is found that, even with volatile solvents such as ether, solvent lost through the connecting funnels is negligible if these are lightly plugged with cotton-wool. There is no mechanical loss through the funnel by any pumping action when the phases are agitated. There is a stopper so that, if required, sampling of both phases can readily be carried out in every tube.

Seen on the Quickfit and Quartz stand at the BIF, the 200-tube Craig machine

The machine chassis is of simple construction, comprising duralumin tubing and stove-enamelled castings. The tubes are attached by specially designed spring clips which facilitate the process of assembly.

An automatic pick-up device, together with a solvent reservoir and flow regulator, provide automatic feeding of the solution to be extracted, or by a simple adjustment the mixture may be recycled through the entire bank of tubes as many times as is desirable.

The machine is normally supplied complete with electric motor, time switch and warning device so that the agitation is carried out mechanically, the other operations being done manually. Designs are also available either for manual operation only or for fully automatic operation during the extraction process. In the latter case the time cycles for stages 1 and 2 are variable over a wide range.

Combined ion chamber for betas, gammas

Intended for the maintenance of standards of radioactive nuclides, a new combined beta and gamma ionisation chamber has recently been introduced by General Radiological Ltd, 15–18 Clipstone St, London W1. The Chamber, known as Type 1383A, is based on the standard designed by the National Physical Laboratory and has been developed under the guidance of the AERE, Harwell.

The ionisation chamber is a combination of a re-entrant cylindrical chamber for the measurement of gamma-ray emitting isotopes and a "parallel plate" type of chamber for measuring beta-ray emitters.

The gamma-chamber consists essentially of three concentric brass cylinders of radii approximately 3·6, 6 and 8 cm respectively, and lengths 13, 16 and 18 cm, the intermediate cylinder being the collecting electrode. The beta-chamber occupies the lower part of this cylinder, the ionised volume being between the dome-shaped electrode and the bottom plate. The beta-rays enter the chamber through a graphited plastic window of thickness 0·001 in. and diameter 4 cm. The source (1 ml of liquid in an alkathene dish) is mounted on a slide, its surface being about 2 cm below the window.

The total ionised volume of the chamber is about 3 l.; the volume of the beta-chamber is about 0·15 l. The capacity is about 25 cm.

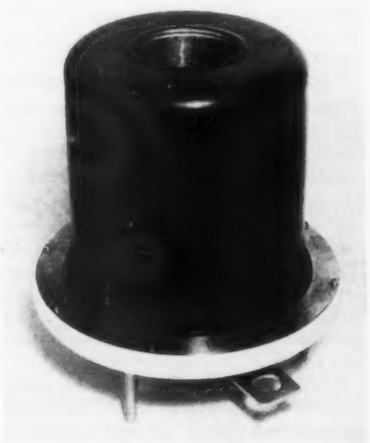
The main characteristics of the chamber as determined by measurement at the NPL are approximately as follows:

(*a*) **Saturation voltage:**
Gamma-ray chamber 100 volts.
Beta-ray chamber 100 volts.

(*b*) **Gamma-ray calibration:**
Radium (platinum tube 250 μg) $4{\cdot}4 \times 10^{-11}$ amp/mg
Radium (ampoules of solution 100 μg, 50 μg, 20 μg) $4{\cdot}8 \times 10^{-11}$ amp/mg
Cobalt 60 (ampoules of solution 1–2 mc) $6{\cdot}4 \times 10^{-11}$ amp/mg
Iodine 131 (ampoule of solution 1 mc in 1 ml) $1{\cdot}58 \times 10^{-11}$ amp/mg

(*c*) **Beta-ray calibration:**
Liquid sources in alkathene dish. 1 ml of solution containing a few μc per ml.
Phosphorus 32 $3{\cdot}5 \times 10^{-10}$ amp/ml
Iodine 131 $0{\cdot}7 \times 10^{-10}$,, ,,
Thallium 204 $0{\cdot}9 \times 10^{-10}$,, ,,

(*d*) **Background:**
The background current is about 10^{-14} amp and is approximately equivalent to the ionisation produced by the following quantities of material:
Gamma-chamber:
0·23 μg Ra, 0·17 μc Co^{60}, 0·7 μc I^{131}
Beta-chamber:
0·03 μc 32_P, 0·12 μc Tl^{204}, 0·16 μc I^{131}



General Radiological's type 1383a ion chamber follows NPL standard

Seeing inside by periscope up to 25 ft away

The Bodson periscope can be had in stainless steel with radiation-resistant lenses

Periscopes for the inspection of dangerous or inaccessible situations manufactured in France by Bodson et Fils of Puteaux (Seine), are now available from the sole British agents: P. W. Allen & Co., 253 Liverpool Road, London N1 (NORth 4665), in addition to the Bodson endoscope, a portable instrument for the internal inspection of tubes in other confined spaces.

The Bodson periscope is normally installed as a permanent part of the plant equipment and should find numerous applications in reactors and other radioactive plant. For these purposes the instrument can be supplied entirely in stainless steel with cerium-stabilised radiation-resistant glass lenses. The normal diameter of the tube is 33 mm and the maximum total length can be about 25 ft. The optical system consists of a series of prisms and lenses and a variety of bends is available to suit circumstances. The field of view is normally 45°–50°, but magnifications up to eight times are possible with the reduction of field to 6°. The apparatus can also be used with a camera. The British agents state that they offer a complete technical advisory service on all visual inspection problems.

U from non-U by ion exchange

Widely used by industry for softening and demineralising water, ion exchange has now been adapted for extracting uranium from low-grade ore. Up till 1939, no low-grade ores were processed for uranium recovery, and even the high-uranium content pitchblende deposits of the Belgian Congo and elsewhere were used almost entirely as sources of radium.

Following the second world war, these rich deposits—containing as much as 70 per cent of uranium oxide—were insufficient for meeting the new and urgent uranium demands, and a world-wide search was made for other high-grade ores. This however was unsuccessful: though uranium is of relatively common occurrence, no more rich deposits were found, and it was therefore necessary to extract uranium from low-grade ores.

Difficulties were soon experienced. Even the richest of these contain less than 0·5 per cent of uranium and extraction by classical methods proved costly, laborious and inefficient. No difficulty was found in dissolving uranium from these ores with dilute acid, but unfortunately many base metals were dissolving at the same time. The liquor thus contained a relatively low content of uranium in the presence of much larger quantities of valueless salts, and no simple and cheap method of separation was known.

For some time, little progress was made until it was discovered that if the leach solution was passed through an anion-exchange column, the uranium was adsorbed on to the resin, whilst practically all other metallic impurities passed straight through the column. This was a completely unexpected result, since metals in general are adsorbed only by cation exchange, and not by anion exchange.

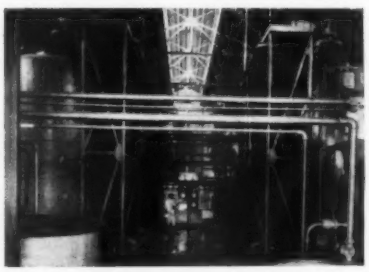
The possibilities resulting from this discovery were of immense importance because—in one simple step—it was feasible to produce a concentrated and relatively pure solution from which the uranium could subsequently be removed by a simple precipitation process. Intensive research was at once put into operation in both Great Britain and the United States; and when the technique involved had been carefully worked out, a pilot plant was installed in South Africa for treating the low-grade uranium ores associated with the Rand gold tailings and deposits.

The results obtained with this pilot plant were, if anything, even more successful than had been expected, and the decision was at once taken to use ion exchange for the uranium extraction process.

Ion exchange materials are substances of complex molecular structure having the ability to exchange or adsorb ions from solutions with which they come in contact. They are commonly used in the form of columns of granular particles through which the solution to be treated is passed: in the familiar application of water softening, cation exchange material is used which exchanges sodium cations for the hardness-forming calcium and magnesium ions, and this softening action continues until all exchangeable sodium ions have been given up to the water. When this point is reached, the ion exchange column is "regenerated" with common salt.

For uranium recovery, the process is generally similar, but a material such as *De-Acidite FF* anion exchange resin is used, on to which the uranium from the pregnant leach liquor is adsorbed in anionic form. This adsorption continues till the resin is fully loaded with uranium: the column is then eluted with an acidified salt solution to strip the uranium, which is subsequently precipitated from the eluate. The final product consists of dry cake containing up to 90 per cent uranium oxide.

Owing to the valuable nature of the pregnant leach liquor, and to the necessity of producing pure eluate with the highest possible uranium value, the liquor is recycled, i.e. it is passed through two, and sometimes three, columns working in series. To reduce the consumption of eluate, elution is also carried out on a recycling basis.



Extraction columns, Port Pirie, Australia

Though the theory of the process was clearly established and results obtained with the South African pilot plant were available, the design and construction of large-scale equipment involved many formidable difficulties. The technique involved was very different from that of water treatment, and there was thus little practical experience on which to base the design. Furthermore, because the solutions to be dealt with were highly corrosive, unusual constructional methods had to be adopted: this aspect was further complicated by the complex flow sheet, and by the need to provide fully automatic controls.

The first full-scale Ion Exchange Uranium Extraction Plants were successfully commissioned in South Africa by the Permutit Company Limited, London, within the time specified. Since then, many more Permutit plants have been supplied both to South Africa and Australia, and others are at present under construction for uranium projects in Canada and Northern Rhodesia.

Dounreay

CONSTRUCTION OF THE EXPERIMENTAL FAST-BREEDER REACTOR at Dounreay on the northernmost coast of the British Isles is proceeding rapidly. On the site, the 135-ft containing sphere is already completed, together with much of the mass concrete work for the reactor foundations and the biological shield. Meanwhile, at the Wolverhampton works of John Thompson Ltd, stainless-steel heat-exchanger loops are in full production and other components are in the course of manufacture.

The Dounreay reactor is essentially experimental and will form the prototype for possible future power stations of this type. It will develop about 60 MW of heat and presumably this will be used to generate some power in a steam turbine, although no details have yet been given of the proposed plant.

The whole of the active part is contained in the huge one-inch-thick steel sphere. This is not intended to resist the force from the unlikely event of an explosion but, designed to withstand an internal pressure of 18 lb/sq in. or a collapsing pressure of 5 lb/sq in., it will be capable of containing any escape of fission products and will also withstand a sodium fire.

Occupying the lower half of the sphere is a massive concrete bowl, 95 ft in diameter and 45 ft high, covered by a concrete slab, thus forming a vault which contains the core pot and entire primary heat-exchanger system. No details are as yet available about the core beyond the fact that it will be only 2 ft in diameter and 2 ft high, and will be composed of a lattice of U^{235} or Pu^{239} surrounded by a breeding blanket of natural uranium or thorium rods. The core assembly is contained in a stainless-steel pot of about $13\frac{1}{2}$ ft diameter and about the same height. The top of the pot is closed by a thick plug of shielding and will incorporate a system of pressurised liquid-cooled eccentric cylinders which can be rotated to control the reactivity and to

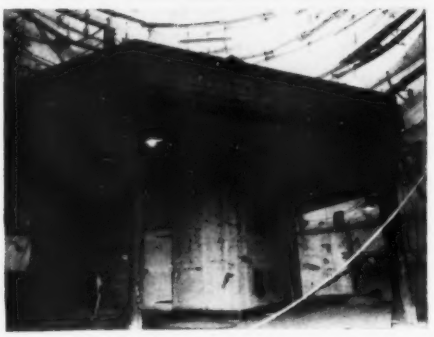
The 135-ft diameter containing sphere is in 1-inch steel plate, welded throughout. On the horizontal diameter is a stiffened ring to receive the top half. Just below this is a stiffened circular opening for the air lock through which access will be gained to the reactor. An impression of the complete plant, with possible future ones in the distance, can be gained from the reproduction of a water-colour by W. Heaton Cooper at the top of the page

align the charging machine for fuel-element changing.

The core pot is supported by a steel structure standing on the base of the concrete vault and is surrounded by a 4-ft thick borated graphite neutron shield incorporating a belt of pure graphite through which the fission rate can be determined down to low levels.

The primary coolant is sodium and the heat released in the core is taken to a battery of 24 heat exchangers arranged not quite radially from the pot and extending inside the vault under the roof slab. Each exchanger consists of a flattened coil of coaxial stainless-steel tubing, the inner pipe being connected to the top and bottom of the core pot by a bellows expansion joint. The secondary liquid is also sodium—possibly with some potassium added—and it flows through the annulus of the primary heat exchangers, each secondary circuit going through two primary heat exchangers in series. Each primary loop has an English Electric electromagnetic pump in the top leg just below the roof slab, while the electromagnetic pumps for the secondary circuit are right outside the sphere. The secondary inlets and outlets are arranged about halfway along the upper and lower horizontal legs of the exchangers, the remainder of the annular space beyond the off-takes

Inside the half-completed sphere the thermal shield begins to take shape. Above, a special tent protects workers from the northern climate



A massive concrete stool at the base of the inner bowl will support the core pot

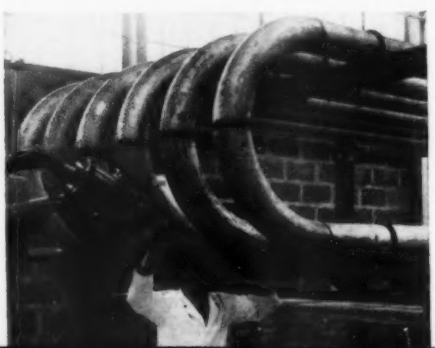
up to the bellows expansion joint being gas-filled, and fitted with leak-detection lines leading to the instrumentation centre. Each loop is fitted with a by-pass cold trap for the continuous removal of oxide, and they are also fitted with short-jacketed heat-exchanger sections which provide a thermo-syphon rejection of shut-down heat to a sodium-air heat exchanger in an external stack should a total failure of electricity supply occur. Of the 24 primary heat exchangers, 20 serve the reacting core while four provide cooling for the blanket. Power for the electromagnetic pumps comes from a battery of diesel generating sets each of which serves only two pumps, so that the failure of one set will cut only one-tenth of the main coolant pumps.

The roof slab of the vault is pierced at the centre by a 20-ft diameter hole round the periphery of which a series of vertical columns support the edge. All the components are designed to pass through this hole. The heat-exchanger loops are all heavily insulated, and the whole vault is kept at a high temperature by means of air heaters. The columns and mass concrete are air cooled through integral ducts.

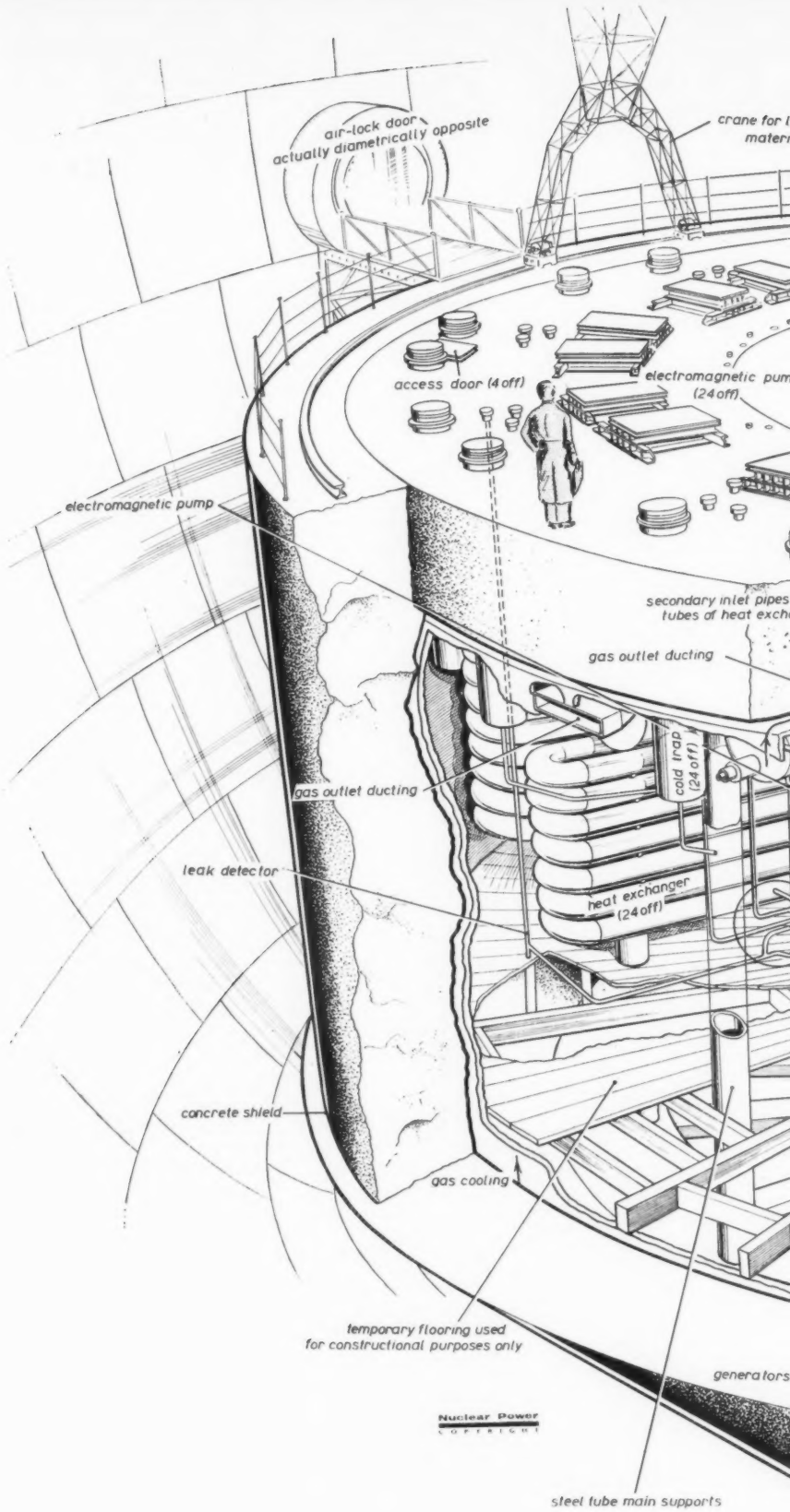
The fabrication of the heat-exchanger elements is interesting. On the straights, the correct annular distance between the two concentric tubes is maintained by three spiders—one at each end and one in the middle. These are machined out of solid stainless steel and have three projections at 120° which support the outer tube. Three of these spiders and two lengths of inner tube welded end to end form one inner leg over which the outer leg—in one piece—is slipped.

All tube ends are turned with a weld preparation. The bends are formed cold from two quarter turns which are slightly rotated before welding in order to give the correct helical angle to the pipe assembly. Argon-arc welding is used throughout, with no backing rings but with an atmosphere of argon inside the tube.

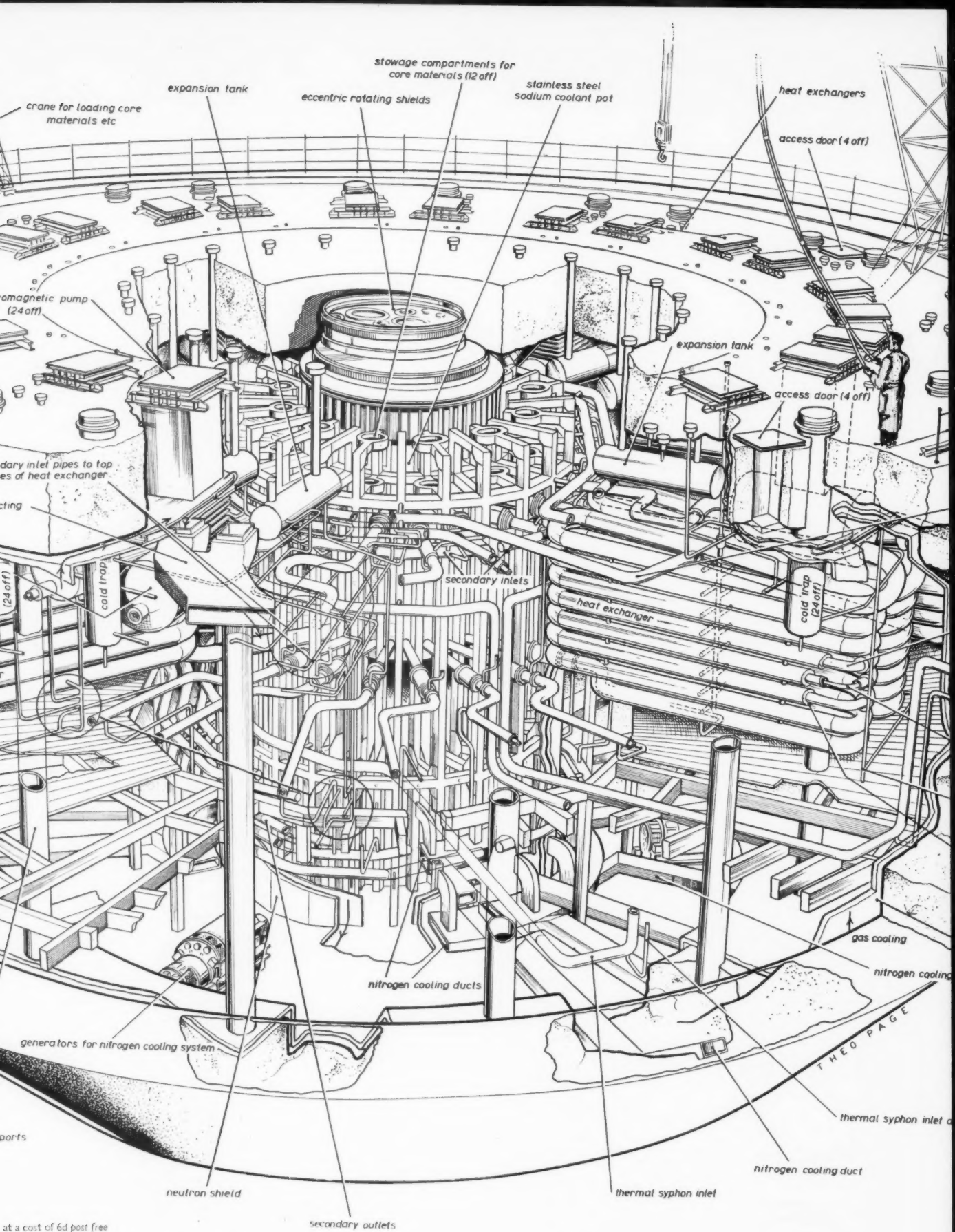
A comprehensive system of inspection is carried out, using a portable x-ray apparatus. Every inch of weld is examined by taking four exposures of each joint, the field of each exposure being 90°. Complete records of these inspections are being kept for future reference. In addition, each weld is leak-tested, using nitrous oxide apparatus capable of detecting 1 p.p.m. of N_2O. It is understood that this test has yet to locate a leak in a component which has already passed the x-ray test.



At the maker's works one of the 24 stainless-steel co-axial heat-exchanging units receives a rigorous x-ray weld inspection



Copies of this drawing may be obtained from *ROWSE MUIR PUBLICATIONS LTD*, 3 Percy Street, London, W.1, at a cost of 6d p



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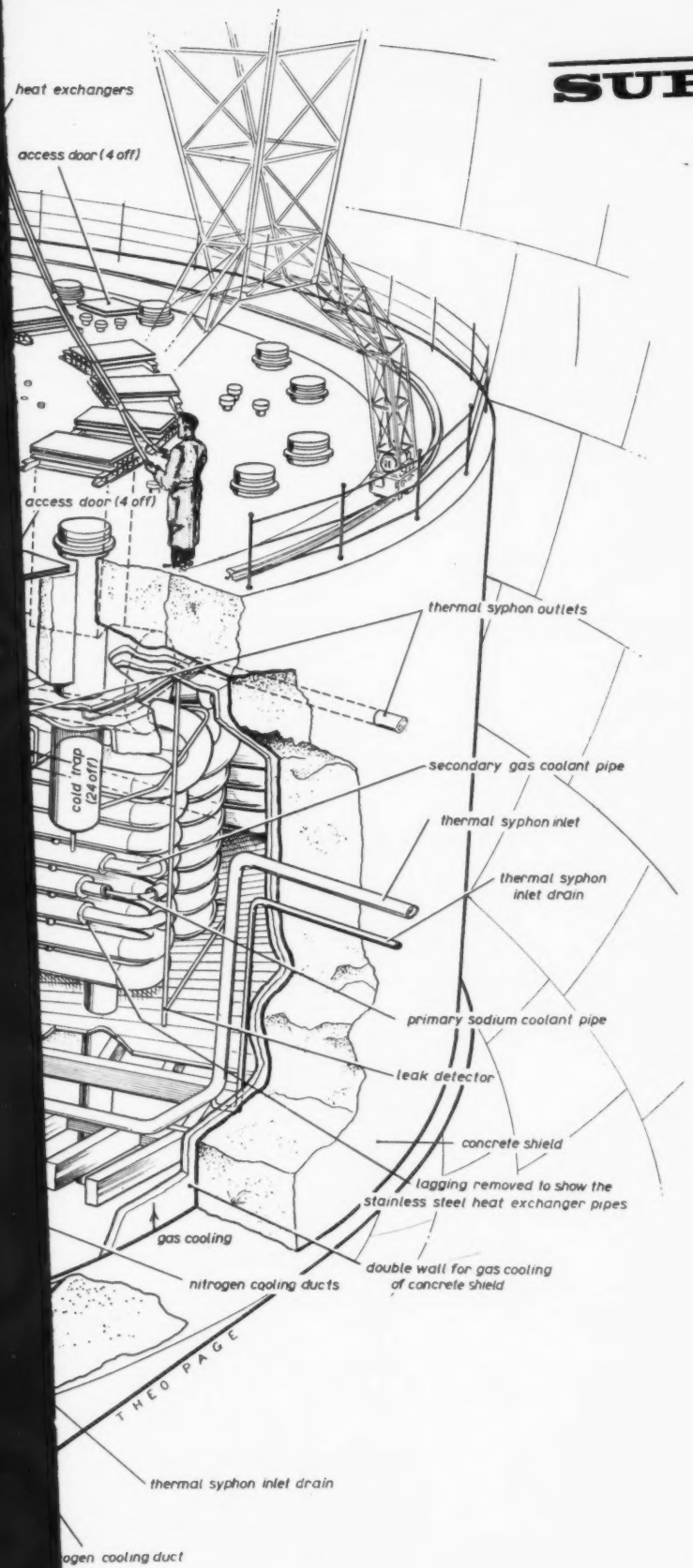
SUPPLEMENT 1

Dounreay fast-breeder reactor



Nuclear Power
The journal of British nuclear engineering
JUNE 1956

For many purposes heat, as such, and not electricity will be needed from nuclear reactors. The early British pile BEPO has been providing space heating for some years

Heating and ventilating at Harwell

by G. M. Harbert
Senior Engineer, AERE, Harwell

At Harwell three sources of heat are now in use, namely: solid fuels, electricity and nuclear energy. The approximate contribution from each and its cost are as follows:

	per cent.	cost per therm
steam from main coal-fired boiler houses	97·0	7·1*d.*
local coke-fired hot-water boilers	0·75	—
electricity	0·9	31·7*d.*
reactor waste-heat	1·35	1·47*d.*

In the case of the latter, the heat is a free by-product of the reactor operation, but some electrical energy is expended in distributing the heat, and in increased air-pumping power due to the resistance of the heat exchanger in the air-cooling circuit.

Although the use of heat derived from the nuclear reactor BEPO appears attractive, it is at present subject to two serious limitations—firstly, whenever the reactor is off power no heat is available; secondly, the temperature of the heat release is relatively low. This means that alternative means of heating need to be provided and in some applications the source is inadequate by itself.

On economic grounds, therefore, steam is the prime source of heat used. It is distributed from central boiler houses at a pressure of 120 lb/sq in. in insulated mains carried in ducts, since considerable importance is attached to appearance at Harwell.

Floor *versus* ceiling

The heating of laboratories has passed through some interesting stages of evolution. The first ones specially prepared for radioactive work in this country were created in existing airfield buildings. Low-pressure hot-water radiators already existed, and these were allowed to remain to provide background heating even in those laboratories where the nature of the work necessitated a high air-change rate.

In planning the first purpose-built hot laboratory—in the radioactive sense—for maximum cleanliness, radiators were rejected in favour of embedded floor coils. This proved extremely satisfactory in service, but the high cost led to a determined search for economy in the next construction phase. The cost of mechanical ventilation on a large scale became an obvious target.

In the next new laboratory block, where the anticipated activity levels were much reduced, it was decided to revert to local extract fans from individual fume hoods or group of hoods, and to provide the main heating by means of radiators of the hospital pattern to afford the best facilities for maintaining cleanliness.

Ceiling panels were also tried. These are capable of operation at much higher temperatures than floor coils and permit a much greater heat release but, particularly in single-storey buildings, they tend to produce hot heads and cold feet.

Pressurised laboratories

As a result of these experiences I have formed the opinion that the correct approach to background heating lies in embedded floor coils whenever anything beyond the minimum of services are to be installed. Expansion of the coils and the effect of localised heat on the floor screed and covering limit the flow temperature to about 110°F, and hence severely restricts the heat release, but it is possible to cater for the fabric losses by this means, the air-change loss being provided by a plenum system. In a new building now under construction, however, where plenum air has certain disadvantages from the operational viewpoint, the air-change loss is being supplied by means of ceiling panels.

The next two large laboratory blocks at Harwell were accordingly designed for floor-coil heating and about two to three air changes per hour, the warmed air being introduced into each room from a duct and allowed to make its own way out through the doors, windows and air bricks, except in those laboratories where the presence of fume hoods necessitated the provision of mechanical extract. Such a system which entails pressurisation of laboratories is permissible only where activity levels are

VARIOUS methods of heating laboratories at Harwell are discussed. Utilisation of waste-heat from BEPO, the natural uranium, graphite moderated research reactor, to provide space heating and hot water is described in some detail and the limitations of the system are related. The trend of mechanical ventilation systems in radioactive laboratories is reviewed and features of some unusual systems are explained, including the use of glass ducts and the operation of axial-flow fans in series to provide high head and so increase the useful life of high-grade filters which, being active, present a disposal problem.

L'AUTEUR étudie les différentes méthodes de chauffage employées aux laboratoires de Harwell. Il décrit avec quelques détails l'utilisation de la chaleur perdue provenant de la pile BEPO (pile expérimentale à l'uranium naturel avec modérateur graphite) pour le chauffage des bâtiments et de l'eau, et en indique les limitations. Ensuite il donne l'aperçu des tendances qu'on trouve dans les systèmes de ventilation mécanique aux laboratoires radioactifs, et explique les traits caractéristiques de quelques systèmes particuliers, tels que l'usage des conduits en verre et l'opération des ventilateurs à courant axial, arrangés en série afin de produire une haute pression, ce qui prolonge la durée utile des filtres de haute qualité qui présentent le problème d'élimination à cause de leur activité.

VERSCHIEDENE Verfahren zur Beheizung der Harwellschen Laboratorien werden erörtert. Die Nutzbarmachung der Abwärme vom BEPO-Reaktor (Versuchsreaktor mit Natururanbrennstoff und Graphitmoderator) für Raumheizung und Warmwasserbeschaffung wird beschrieben, und es wird über Begrenzungen des Systems berichtet. Die allgemeine Entwicklungsrichtung der mechanischen Ventilationseinrichtungen in radioaktiven Laboratorien wird besprochen; ausserdem werden Merkmale einiger ungewöhnlicher Systeme erläutert, u.a. Verwendung von Glasleitungen sowie von hintereinandergeschalteten Axial-Ventilatoren, wodurch ein hoher Druckwert erreicht wird; die Nutzungsdauer der hochwertigen Filter, deren Aktivität das Wegschaffungsproblem mit sich bringt, wird infolgedessen verlängert.

SE DISCUTEN varios métodos para la calefacción de los laboratorios en Harwell. Se describe en detalle un sistema para la provisión de calefacción y agua caliente, utilizando el calor residual de BEPO, el reactor de uranio natural moderado por grafito, y se señalan sus limitaciones. Se pasa revista de los sistemas de ventilación mecánica actualmente en uso en laboratorios radioactivos, y se explican las características de algunos sistemas no empleados usualmente, incluyendo el uso de conductos de vidrio y la operación de ventiladores de corriente axial en serie a fin de proveer una presión alta y así prolongar la vida útil de los filtros de alta calidad que, siendo activos, introducen el problema de enajenación.

ОБСУЖДАЮТСЯ различные методы отопления харвеллских лабораторий. Описывается использование теплоты, отводимой из экспериментального уран-графитового реактора BEPO для отопления помещений и нагрева воды; указываются ограничения этой системы. Дается обозрение общих направлений развития установок для механической вентиляции радиоактивных лабораторий; об'ясняются детали некоторых не шаблонных систем, в том числе применение стеклянных трубопроводов и действие последовательно соединенных вентиляторов осевого тока, с целью создать высокий напор и таким образом продлить срок службы высококачественных фильтров, которых активность ставит проблему удаления.

low, as the risk of air drift from one room to another with the consequent transfer of activity cannot be altogether excluded.

Shortcomings of BEPO

The source of nuclear energy available is the British Experimental Pile, BEPO, a natural-uranium, graphite-moderated, air-cooled reactor with a nominal output of 6000 kW. Heat generated in the uranium slugs is transferred to an air stream drawn through the reactor, but as this air becomes radioactive it is not suitable for direct use for space heating and must be discharged up a 200-ft high stack to ensure dispersion.

By introducing a heat exchanger into the system it is, however, possible to transfer the heat to a water circuit. The design of this particular reactor limits the temperature obtainable in the water circuit to 160°F, the heat exchanger having been chosen to provide the maximum water temperature consistent with low draught losses and hence the greatest economy in air pumping power.

This, then, is the hot water available for space heating; barely hot enough for radiators, which are normally designed for a flow temperature of 180°F; too low for re-transfer to air in plenum systems; and too hot for use in floor coils. In addition, alternative sources of heat need to be provided to allow for the days on which the reactor is off power for charging and discharging operations.

The systems in which this heat is used have therefore been designed to meet the following conditions:

(*a*) facilities for operating from steam are retained;
(*b*) the maximum use to be made of pile heat, but if it is insufficient the deficiency to be supplied by steam;
(*c*) the change over from steam to pile heat and *vice versa* to be entirely automatic;
(*d*) the possibility of reverse heat transfer from steam to the pile heating fluid must be precluded.

The use of the heat from BEPO for space heating has been developed in three stages and is now successfully applied to several large buildings with a nominal total heat demand of 6·5 million B.t.u./h, comprising floor coils, radiators and hot-water services.

Water is circulated through a gilled copper-tube heat exchanger of conventional design, with a duty of $7{\cdot}5 \times 10^6$ B.t.u./h, by an electrically driven centrifugal pump capable of delivering 500 gal/min against a total head of 65 ft. This pump which has been installed in the flowline in order to reduce the pressure on the heat exchanger is started remotely from the pile control room when the reactor is on load. The hot water is circulated to the buildings selected for this service in steel mains lagged with sectional asbestos and run in underground ducts which had already been built to carry steam, condensate and compressed-air mains.

The building chosen for the first stage provided a floor coil load and a hot-water system. In both cases a water-to-water calorifier has been introduced between the return flow and the steam-to-water calorifier, the former being shunted by a three-way mixing valve. Referring to the flow diagram (Fig. 1), when the valve is in position A, the flow is from the circulating pump through the by-pass and thence the steam-to-water calorifier; in position B the flow from the circulating pump is through the water-to-water calorifier and then through the steam-to-water calorifier. Intermediate positions of this valve allow a

proportion of the flow to pass through the water-to-water calorifier before entering the steam-to-water calorifier. Let the fluid temperatures be defined as follows:

Flow from the pile heat exchanger	T_1
Return flow from the building heat load	T_2
Inlet to steam-to-water calorifier	T_3
Flow to the building heat load	T_4

When the mixing valve is in position A, $T_2 = T_3$.

High cost of distribution

If we now consider the application to a floor-coil system, then T_4 must not exceed 110°F and T_1 must not fall below T_2 if reverse heat flow is to be avoided. When the reactor is not operating, T_1 will clearly be less than T_2 so that the mixing valve takes up position A and the heat load is met by the steam-to-water calorifier in the ordinary way. As the pile is put on power and the main circulating pump started, T_1 will increase until it exceeds T_2, whereupon the mixing valve moves into position B, and when T_3 reaches the design temperature for T_4 the steam supply to the steam-to-water calorifier is shut off. An increase in temperature of T_4 over 110°F causes the mixing valve to move into an intermediate position so that only part of the building return flow passes through the water-to-water calorifier, thus limiting the heat absorbtion. On closing down the reactor, T_1 falls until it is less than T_2, whereupon the mixing valve returns to position A and steam is restored to the steam-to-water calorifier by the thermostatic control.

If the reactor should be operating on low power so that T_3 does not reach the correct level, the additional heat is derived automatically from the steam-to-water calorifier. The application to hot-water supply services follows the same principles.

In the second stage, the hot water from the pile heat system has been introduced into radiators without the intervention of a heat exchanger. This has been done by inserting connections to the pile heat mains between the building circulating pump and the return-flow connection to the steam-to-water calorifier, together with the usual by-pass. This arrangement was adopted to make as much use as possible of the limited pile heat flow and to save the cost and space occupied by an additional heat exchanger. It has, however, the disadvantage of increasing the pressure on the internal heating installation; initially this resulted in a number of leaks in radiators and causes difficulties if the system is not completely vented.

In common with all district heating schemes, it is the high capital cost of the distribution mains that detracts from the economic advantages of a central source of cheap heat. In this case the cost of the mains amounted to 45 per cent of the total expenditure, although they were run entirely in existing ducts.

Glass ventilation ducts

In early radioactive laboratories the air-change rate was a function of the number and size of fume cupboards installed, since the minimum safe face velocity determined the quantity of air to be extracted from each one. Moreover, as no portion of the extract could be recirculated owing to the possibility of the air still containing some degree of activity in the form of gas or suspended particles, it was found in practice to be very expensive in operation, in heat lost rather than in fan power.

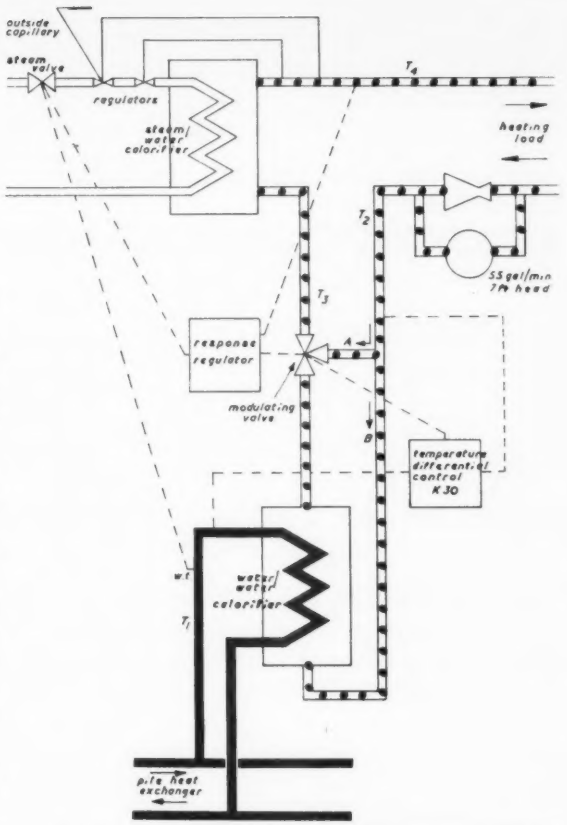


Fig. 1 *The space heating system using BEPO is integrated with a conventional steam plant, switching from one to the other being fully automatic*

The use of dry boxes, in which hazardous operations are carried out by personnel working in rubber gloves sealed into the box face, diminishes the air quantity to be handled to so small a value that the air-change rate in the laboratory can be determined independently. This rate is settled in consultation with the health physicists having regard to the nature of the work. Present-day practice, for laboratories in which it is expected hot work will be carried out in dry boxes, is to design the general ventilation to provide about ten changes per hour. The high air change rates associated with high-activity work in open-fronted fume cupboards is now quite outmoded in all new laboratories.

Considerable importance should be attached to the correct positioning of air input and extract grilles relative to one another in order to ensure that the whole working space is swept by the air movement. In the first building at Harwell in which dry boxes were used, and freedom of choice for the location of grilles was afforded, the air was introduced at low level, having been led down in ducts fixed to the wall face between adjacent windows from a void above, and extracted through ceiling grilles at the opposite side of the room.

In due course it was decided to extend this building, but the architect wished to follow the fashion of extensive glazing and omit the wall between windows on which the

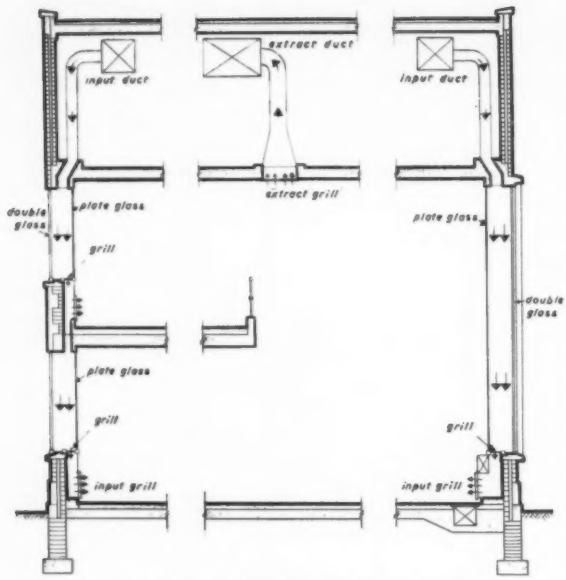


Fig. 2 *In a new laboratory the walls are extensively fenestrated, and the fresh-air ducts are formed by what amounts to treble-glazed windows*

input air ducts had been fixed in the original design. I therefore decided to construct the duct in glass (Fig. 2). This was achieved by double glazing the whole wall on the outside and fitting an inner lining of plate glass from ceiling down to a low-level grille; the plenum air is introduced from a duct in the roof void to the space between the plate glass and patent double glazing at very low velocity. The system involved some constructional difficulties in getting the air connections round the structural steelwork carrying the wall of the upper floor, but has proved quite satisfactory in operation.

Prolonging filter life

Considerable controversy has raged over the relative merits of centralised versus individual ventilation plants. The latter tend to appear deceptively attractive on the grounds of saving the construction of plant rooms and runs of ducting, and find favour in the eyes of many scientists by virtue of full local control, but in my opinion it is not an economic arrangement except in the case where mechanical ventilation is required in only a few rooms widely dispersed in a large block.

A multiplicity of such plants does give rise to the very real risk of the discharge from one system being mixed with the fresh-air inlet to another. Although the individual equipment system has, I believe, been used in the USA, it has not been adopted here apart from a few instances where only tracer activity levels have been handled.

A compromise has, however, been employed recently in the design of a number of new laboratories built at the Radiochemical Centre at Amersham. Here, for reasons of shielding, it was decided to erect four laboratories, with provision for a further four later, as separate buildings to afford mutual shielding. Each laboratory was provided with its own plenum fan, but a single central extract plant only is housed in a small plant room and the exhaust gases are discharged up a 54-ft high stack. Each plenum fan can operate at two speeds, as can also the extract fan, thus allowing the maximum economy to be effected in running costs. This system is proving very satisfactory in service.

One of the major costs in running certain radioactive research laboratories has been the renewal and disposal of the sub-micron filters fitted in the contaminated extract systems. Due to the radioactive nature of the dust particles in the filter medium, it is not possible for them to be disposed of in a normal manner and, as some thousands of these units are involved, this presents quite a headache to the maintenance staff. It was therefore decided to investigate the possibility of prolonging the life of these filters by allowing the pressure drop across them to increase. This necessitated the provision of a fan with a more or less constant output, but with a varying pressure characteristic in order to overcome the increasing resistance.

The most suitable fan, taking all things into consideration, is the axial-flow. Two types were considered; first, the "purpose made" multi-stage variable-speed; second, the standard commercial single-stage, a number of these units being arranged in series so as to attain the desired maximum water gauge. Either of these would have satisfied the technical requirements, but when cost was considered it was apparent that standard commercial units in series were by far the cheapest.

As these fans were built into a contaminated extract system and the motors contained within the air stream, they had to be of totally enclosed manufacture and specially protected against temperature rise. Special care had to be taken with the electrical connections so as to ensure that the joint between the connecting box and the casing was airtight. In arranging the fans, it was decided to take advantage of the contra-rotation and five single-stage units were set up in series to provide such an arrangement.

A conversion problem

It sometimes occurs that the ventilating engineer can provide a simple answer to a problem primarily associated with another field of engineering. As an example, two large compressors, each driven by a 75-hp motor, were required to be converted from the compression of nitrogen to hydrogen, which is an excluded gas for the purpose of flameproof enclosures as defined in BSS 229, and in any event motors already existed.

It was therefore decided, instead of moving the motors into a separate room, to construct a steel housing around them in their original position and to pressurise the inside with fresh air drawn from outside and discharged also outside the danger area. Air at a sufficient rate to remove the heat losses from the machines is introduced by means of an axial-flow fan, which keeps the whole circuit slightly above ambient pressure, so that air leaks out rather than hydrogen in.

I would like to record my thanks for the help given by my colleagues in the preparation of this paper*; I am also grateful to the United Kingdom Atomic Energy Authority and the Ministry of Works for permission to publish it.

* This article is an abridged version of a lecture given by Mr Harbert to the Institute of Heating and Ventilating Engineers in London on 21st March, 1956.—Ed.

For certain nucleonic instruments, transistors offer important advantages over thermionic valves.

a NUCLEAR POWER correspondent reviews recent British papers

Transistors in nuclear instruments

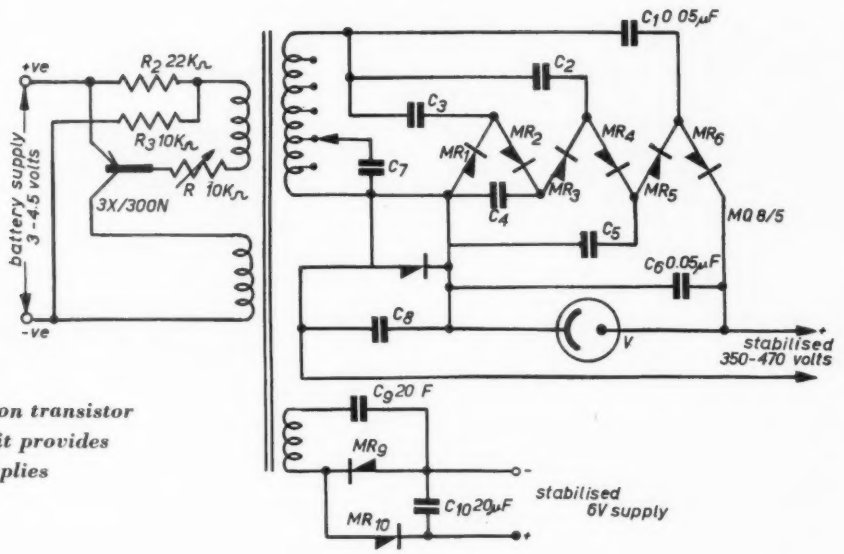


Fig. 1 *A junction transistor oscillator circuit provides HT and LT supplies*

Transistors are now finding application in many nuclear instruments. From the circuit designers' point of view they offer the advantages of small size and low power requirements as well as potentially good reliability. The lack of heaters enables full advantage to be taken of the small size of the transistor in designing compact equipment. In addition, the low HT supply voltage (about 10 volts) and the relatively small current drain considerably simplifies the power-supply problem.

A good example of the low power requirement can be illustrated by referring to the high ratio of power supplied to the load to power dissipated in the transistor, possible with two-state circuits. DC converters of this type can be designed using transistor circuits with an over-all conversion efficiency as high as 80 to 90 per cent. In the past, either high-voltage batteries (of the order of 400 volts) or DC converters using mechanical vibrators and fed from a low-voltage battery (*e.g.* a flashlamp battery) have been used. High-voltage batteries are bulky and expensive, whereas DC converters using mechanical vibrators have limited life and often relatively low conversion efficiencies. The DC converter using a transistor has thus quite clear advantages, particularly in the case of portable instruments.

A number of nuclear instruments using this type of power supply are now available commercially, and recently E. Franklin and J. B. James read a paper dealing with this and other matters, entitled *The Application of Transistors to the Trigger, Ratemeter and Power Supply Circuits of Radiation Monitors* (Paper No. M2049—The Institution of Electrical Engineers, 27th March 1956).

The power-supply requirements for portable survey meters using Geiger counters are usually quite low. For example, the power required for the operation of the instruments discussed in the above paper is of the order of 10 milliwatts. However, transistors can be used at higher powers, and in another recent paper (*Transistor D.C. Converters*, by L. H. Light and P. M. Hooker, Proc. Inst. Elec. Engrs, 102, Part B, pp. 775–786, November 1955) circuit designs are given for converters ranging in output power from a fraction of a milliwatt to several watts. The paper concludes that the transistor DC converter provides a convenient and efficient solution to the problem of generating high voltages from batteries at power levels up to several watts, that they fill a long-existing need for a practical way of doing this at power levels of the order of a milliwatt, and that they promise to be superior to existing methods at powers of a few watts on the counts of size, weight, reliability and life. They are, however, subject to the usual temperature limitations associated with semiconductors, at least, until such time as silicon transistors become available. The germanium transistors cannot be used satisfactorily above about 60°C.

Figure 1 shows the type of stabilised power supply suggested by Franklin and James for use with a radia-

* This circuit was first described in a paper by H. Bisby, E. Franklin and D. Taylor, entitled *Instrumental Developments in the Prospecting, Mining and Chemical Processing of Nuclear Materials*, read at the International Conference on Peaceful Uses of Atomic Energy, Geneva, August 1955.

TRANSISTORS are finding many applications in modern nuclear instruments. This is because of the advantages they offer of small size, low-power requirements and good reliability. This article outlines the development of high-voltage power supplies for Geiger counters, of radiation monitors and scalers using these new components. It refers to a number of recent papers on the subject, and, in particular, to some presented at a recent meeting at the Institution of Electrical Engineers in London.

LES TRANSISTORS trouvent à présent de nombreuses applications dans les instruments modernes de physique nucléaire; les avantages de leur emploi sont dus à leurs petites dimensions, petite consommation d'énergie et régularité de fonctionnement. L'article esquisse le développement des dispositifs fournissant l'énergie de haute tension aux compteurs Geiger et des moniteurs et échelles de radiation, dont la construction contient ces éléments nouveaux. On cite de nombreux articles récents sur ce sujet, en particulier quelques mémoires présentés à la récente Conférence de l'Institution of Electrical Engineers de Londres.

DIE TRANSISTOREN finden in modernen Instrumenten für kernphysikalische Untersuchungen vielerlei Verwendung. Ihre Vorteile sind: kleine Ausmasse, niedriger Leistungsbedarf und genügende Zuverlässigkeit. Es wird im Aufsatz die Entwicklung der diese neuen Teile enthaltenden Hochspannungenergie-Versorgungseinrichtungen für Geiger-Zähler sowie Strahlungsmonitoren und Umzählvorrichtungen beschrieben. Ausserdem wird es auf mehrere diesbezügliche moderne Veröffentlichungen verwiesen, insbesondere auf einige Berichte, die während der neulich stattgefundenen Versammlung der Institution of Electrical Engineers in London vorgelegt wurden.

LOS TRANSITORES tienen muchas aplicaciones en los instrumentos nucleares modernos, debido a las ventajas ofrecidas por su tamaño pequeño, la potencia reducida que requieren y su funcionamiento seguro. Este articulo delinea el desarrollo de las fuentes de potencia de alto voltaje para contadores Geiger, monitores de radiación y escalimetros que utilizan estos nuevos componentes. Se refiere a un número de publicaciones contemporáneas sobre el particular, especialmente a algunas presentadas en una conferencia reciente de la Institución de Ingenieros Eléctricos (Institution of Electrical Engineers) en Londres.

ТРАНСИСТОРЫ находят многообразное применение в приборах ядерной физики. Это вызвано следующими преимуществами: малые размеры, небольшое потребление мощности и достаточная надежность. В статье описывается эволюция содержащих эти новые части источников высоковольтной мощности для счетчиков Гейгера, а также мониторов и пересчетных схем. Упоминаются также многие современные статьи на эту тему, в особенности доклады, представленные во время собрания, состоявшегося недавно в лондонском Институте Инженеров-Электротехников.

tion monitor using a Geiger counter. It will be noted that stabilised HT and LT supplies are provided, the latter being for the operation of the trigger and ratemeter circuits of the monitor.

DC converters using transistors are also finding application in charging units for quartz-fibre dosimeters. Quartz-fibre dosimeters are very compact instruments and it is convenient to have a compact charging unit. This can be provided using a transistor circuit and one design for such a charging unit is shown in Fig. 2. It provides a DC voltage of 300 suitable for charging and setting up the standard quartz-fibre dosimeters available in this country. It also provides illumination to permit the graticule of the dosimeter to be clearly seen during the setting-up operation.

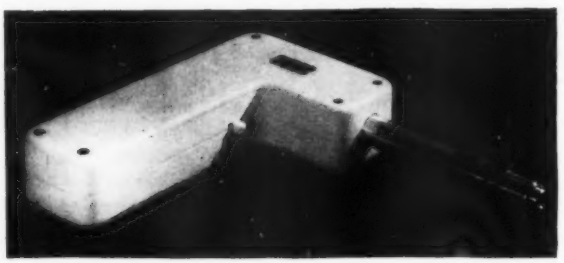


Fig. 2 ***A charging unit for quartz-fibre dosimeters***

Transistors are also being used in the trigger and ratemeter circuits of radiation monitors. For instruments which need to be portable, *i.e.* carried by hand, the advantages offered by small size and weight are real, and many of the recently developed survey meters for health hazard evaluation in the laboratory, for uranium prospecting and for radiological defence purposes are using these transistor circuits. For example, a recently developed geological prospecting instrument using these circuits with both meter and aural indication weighs only $2\frac{1}{2}$ lb as compared with about twice this weight for conventional instruments of the same performance.

Figure 3 shows a typical junction transistor trigger and ratemeter circuit* triggered from a Geiger counter. It will operate in this way over a temperature range of $-20°C$ to $+60°C$. This same basic circuit is being used in many other types of equipment, including borehole logging instruments. It is particularly convenient in this case because the trigger circuit can be kept above ground. The probe would contain only the Geiger counter with its discharge limiting capacitor and resistor, a pulse transformer to match the counter into the cable and a capacitor to decouple the pulse circuits from the Geiger counter tube power supply. A small and compact probe is therefore possible.

Transistor circuits can also be employed in radiation monitors using scintillation counters. Franklin and James, in the paper already mentioned, indicate how the circuit shown in Fig. 3 can be adopted for this application.

Transistors are also beginning to be used in scaling circuits. It is agreed by most authorities that the most

* Full details of this circuit are given in the paper by Bisby, Franklin and Taylor already mentioned.

generally useful scaler for nuclear work is one with a resolving time (the minimum separation between adjacent input pulses that the circuit can accept without counting them as a single pulse is 1 to 2 microsec.). Faster scalers, with a resolving time of the order of 0·1 microsec, are occasionally required, but it is considered that this requirement is met by using a fast pre-scaler in front of the standard scaler. For Geiger counters it is possible to use a scaler with a resolving time as poor as 250 microsec., and special-purpose scalers of this type are much used in the atomic energy establishments, but for the general-purpose equipment a resolving time of 1 to 2 microsec. seems to be the best compromise.

Resolving times of 250 microsec., corresponding to a counting rate of 4 kc/sec can be conveniently attained by cold-cathode scalers, and rates up to several hundred kilocycles per second can be attained by magnetic devices or junction transistors, but for rates in the region of megacycles per second, the thermionic valve has had no serious competitor. However, in two recent papers submitted to the Institution of Electrical Engineers: *A Point-Contact Transistor Scaling Circuit with a* 0·4 *microsec. Resolution* (Paper R2064) by G. B. B. Chaplin, and *A Junction-Transistor Scaling Unitwith* 2 *microsec. Resolution* (Paper R2076), by G. B. B. Chaplin and A. R. Owens, details are given (as will be apparent from the title) of transistor circuits which compete in speed of operation with thermionic valves. Features which contribute to the short resolving times are the prevention of bottoming of collector potential and the absence of capacities. Figure 4

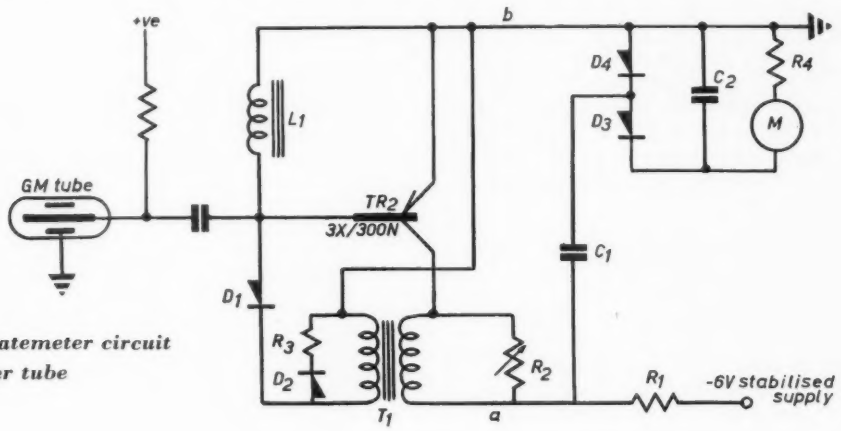


Fig. 3
A junction transistor ratemeter circuit triggered from a Geiger tube

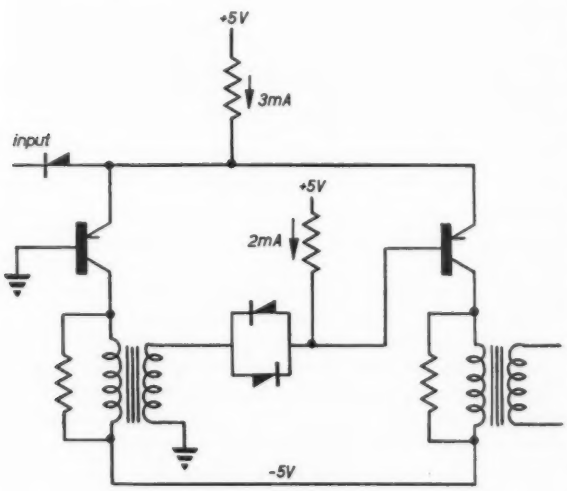


Fig. 4
A binary scaler using point-contact transistors

shows a binary scale-of-two of the type recommended by Chaplin using point-contact transistors. A complete scale-of-ten would comprise a scale-of-two followed by ring-of-five. The resolution of the complete circuit is determined by the binary scaler and is 0·4 microsec., and in all the circuit requires 7 transistors, 7 transformers, 14 diodes and 9 resistors and the power consumption is about 120 milliwatts. At present-day prices the cost of the components for a scale-of-ten of this kind (neglecting the power supply) is about £16. This is to be compared with about £5 for the equivalent valve circuit, again neglecting the power supplies. It would seem therefore that to compete on price the cost of transistors must be very much reduced, According to the manufacturers this will happen. However, it should not be forgotten that the power requirements for a scale-of-ten using thermionic valves may be several tens of watts, and so the cost of the power supplies for a transistor scaler will be very much less than that of the corresponding valve scaler of equivalent performance. Even so, it has to be admitted that a general-purpose scaler using transistors would be more expensive than the corresponding valve scaler. For portable scalers the transistor offers unique advantages, and where portability and battery operation are required it is likely to be the first choice.

Uranium metal-working processes are based on established techniques but need special precautions

The production of reactor

Processes basically similar to those outlined for uranium can also be used for producing thorium or plutonium in the form of billet, although modifications must be introduced to allow for differences in melting-point. In addition, plutonium production and fabrication processes must take account of the high alpha-activity of this metal, which necessitates remote handling processes. Alternatively, by suitable modifications to the later stages, powder may be produced. The methods of production of powder have generally taken the form either of oxide reduction or electrolysis, and processes of considerable promise of a kind shown diagrammatically in Figs. 1 and 2 have been developed on a small scale. They are particularly suited to thorium because of its high melting-point and great reactivity to crucible materials. In general, however, the fabrication processes developed for all three metals exhibit very great similarities and uranium will be taken as the example.

The particular method of fabrication and alloying used for uranium metal depends on the form of fuel element required. Earlier types of reactor, most of which were based on natural uranium, required very pure uranium in highly concentrated forms, and the fuel elements were usually in the form of round bar of varying lengths, fabricated and canned separately with bonded or unbonded can, according to the personal opinion of the

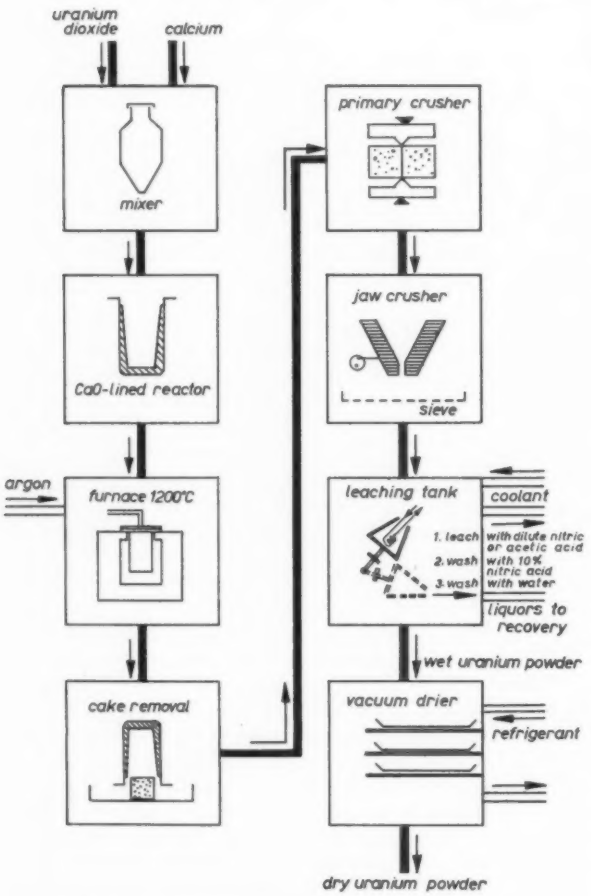


Fig. 1 *Uranium dioxide is processed to dry uranium powder by reduction with calcium*

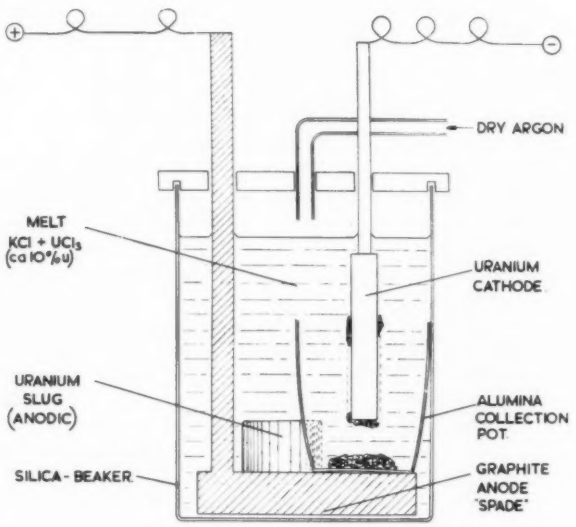


Fig. 2 *An alternative method of reduction is by electrolysis*

designer. Several different techniques of fabrication have been used, but in almost every case the process started with casting, either to convert the reactor billet into the shape of the final fuel element required or into a shape suited to a metal-working process such as rolling or extrusion. In a few cases, however, when special care is taken in the extraction process, it has been found possible to produce a billet which is satisfactory for direct processing. Fuel elements made in this way contain between 8 and 10 ppm hydrogen which is picked up from the reactor materials and atmosphere during reduction.

Vacuum casting reduces this hydrogen, which can otherwise be removed only by lengthy vacuum heat-treatments

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fuel elements – II

WHEN uranium metal has been obtained by the processes outlined in the previous article, it has to be fabricated into fuel elements. This generally commences with high-frequency vacuum casting and the process is described in detail. Further working is then done by rolling or extrusion, using established techniques with modifications. Irradiation in a reactor causes severe distortion and methods have been evolved for minimising this. The use of alternative forms of fuel elements such as sintered ceramics is discussed and a hydrostatic process is described. A third article in this series will deal with plutonium fabrication and fuel-rod canning.

including, preferably, interphase cycling to promote diffusion. The development of suitable vacuum-casting furnaces has however been contemporary with the development of nuclear energy, and a great deal of the stimulus for developing such furnaces has been produced by atomic energy itself. When, therefore, the first fuel elements were required, vacuum-casting furnaces suitable in size and reliability for production use were rare. Under these circumstances the first fuel elements and fabrication billets were cast in open furnaces. The first melting operations were carried out under a flux of barium chloride which does not react with uranium. By careful mould and launder design it is possible to make very satisfactory castings

APRÈS l'extraction de l'uranium métallique au moyen des processus décrits dans l'article précédent, l'uranium doit être transformé en éléments combustibles. On commence en général par la fonte à vide, lequel processus est décrit en détail. Ensuite on façonne les pièces de fonte par laminage ou étirage, en employant des techniques ordinaires avec quelques modifications. L'irradiation dans le réacteur cause une distorsion considérable; on a développé des méthodes qui réduisent cet inconvénient. Finalement on discute l'emploi d'autres formes d'éléments combustibles, tels que des matériaux céramiques frittés, et l'on décrit un processus hydrostatique. Le troisième article de cette série va traiter du façonnage du plutonium et du gainage des barres de combustible.

Fig. 3 ***Air-melt casting can give good results but is prone to oxidation troubles***

NACHDEM Uranmetall gemäss den im vorhergehenden Artikel geschilderten Prozessen erhalten worden ist, muss es in Brennstoffelemente umgearbeitet werden. Dies beginnt gewöhnlich mit Vakuumguss, und wird der diesbezügliche Prozess umständlich beschrieben. Weitere Formgebung geschieht durch Walzen oder in Strangpressen, indem Abänderungen der üblichen technologischen Verfahren angewandt werden. Bestrahlung im Reaktor verursacht starkes Verziehen; man hat Verfahren ausgearbeitet, die diesen Nachteil auf das kleinste Mass zurückführen. Die Verwendung von Brennstoffelementen in anderen Formen, wie z.B. gesinterte keramische Massen, wird erörtert, und es wird ein hydrostatischer Prozess beschrieben. Im dritten Aufsatz dieser Serie wird über Plutoniumaufarbeitung und Umhüllung von Brennstoffstangen berichtet werden.

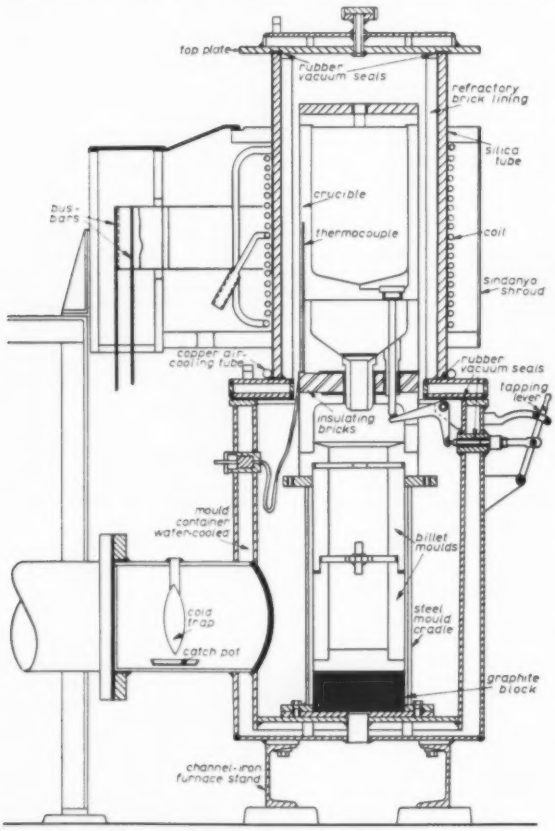
EL METAL de uranio obtenido por los procesos delineados en el articulo anterior debe ser transformado a elementos de combustión. Generalmente se comienza con la fundición a alto vacío y se describe el proceso en detalle. Se continua trabajando el metal por laminación o extrusión, utilizando técnicas ya establecidas con ciertas modificaciones. La irradiación en un reactor causa distorciones graves y se han desarrollado métodos para reducirla al mínimo. Se considera el uso de elementos combustibles de otras clases, como ser el material cerámico calcinado y se describe un proceso hidrostático. El tercer articulo de esta serie tratará sobre la fabricación de plutonio y el envasamiento de barras de elementos combustibles.

by this method provided the crucible is sound, but the electrode graphite normally used for this purpose is often porous and the barium chloride runs down through the crucible and mixes with uranium in the casting. The casting technique was improved by replacing the barium chloride cover by an atmosphere of argon produced simply by directing an argon tube at the top of the uranium. This gave reasonably satisfactory casting, but oxidation of the pouring stream always occurs, however closely the crucible, launder and mould fit together. Fortunately uranium has a low heat of fusion; it solidifies extremely rapidly and so there is little oxidation once it is in the mould. However, the process of air-melt casting (Fig. 3) has been abandoned

КОГДА металлический уран получен путем процессов, описанных в предыдущей статье, нужно из него изготовить элементы горючего. Этот процесс начинается обычно отливкой в вакууме, которая подробно описывается. Дальнейшая формовка производится прокаткой или выдавливанием, с применением несколько модифицированных обычных приемов. Облучение в реакторе вызывает сильное искривление, в виду чего разработаны методы для крайнего уменьшения этого недостатка. Обсуждается употребление других форм элементов горючего, напр. спекшихся керамических масс, а также описывается гидростатический процесс. В третьей статье этой серии будет рассматриваться переработка плутония и снабжение элементов горючего кожухами.

in favour of vacuum-casting, which has proved highly efficient and extraordinarily versatile. Cylindrical bars up to 6 ft long and $\frac{1}{2}$ in. diameter have been produced and castings weighing $\frac{1}{4}$ ton have been made, with some faces left as cast. At the other extreme, castings with ruling section $\frac{1}{20}$th of an inch have been produced—in some cases many thousands at a time.

High-frequency vacuum furnaces may be either of the tilting or the bottom-pouring type. Several varieties of tilting furnace are available and have been proved satisfactory in use, but they require a large vacuum container and great care in design to couple the high-frequency current to the crucible, and they are satisfactory only in comparatively small sizes. Most of the uranium cast has been carried out in a stationary crucible, bottom-pouring



type of furnace (Fig. 4). The major components are a water-cooled bottom chamber which is evacuated through a large-diameter pipe and a top consisting of a silica tube around which is placed the induction coil. A water-cooled steel plate closes the top end of the silica and the bottom end is attached to a water-cooled steel ring. All vacuum joints are made with rubber rings, greased with vacuum grease and where necessary are compressed-air cooled. The seal between the water-cooled ring and the lower water-cooled chamber is the only one that is broken in use, and the top half of the assembly is lowered on to this by means of guides. The coil is a water-cooled copper tube and connections to this are made by means of bus-bars which are bolted to main busbars after the furnace bell is lowered into position. Inside this main outer container is built the casting assembly.

The most suitable material for melting uranium is electrode graphite. Where the material to be cast is an alloy of uranium of high melting-point or one which would react rapidly with graphite, it may be necessary to use a refractory oxide instead. The least reactive of these is uranium oxide, and then beryllia, zirconia, lime and thoria. These materials are, however, all expensive and brittle, and not very satisfactory for commercial production. Where one of them must be used, it is better to support it on a graphite crucible which is also the susceptor. The base of the crucible is pierced by a pouring hole and closed during melting by a graphite or alumina bung. When the molten charge has reached a satisfactory temperature the bung is removed by means of a graphite rod and a system of bell cranks, push rods and levers and the molten uranium runs through a launder into the mould.

The process removes considerable metallic and non-metallic inclusions. Any oxide and fluoride present floats to the top and hydrogen gas is reduced to about two parts per million. High vacua are not necessary for commercial production—0·5 mm Hg is satisfactory for normal purposes—but in special cases high vacua are possible by using a diffusion pump. For mass production of simple shapes the most satisfactory mould material is mild steel. This must be protected from the uranium by a refractory dressing, preferably of alumina, which also acts as a thermal barrier during solidification and prevents cold shuts.

With steel dressed with alumina, very high-quality casting surfaces and close limits of accuracy may be obtained. For example, in the production of hollow tube in tubular-steel moulds, using high-quality graphite cores of 1 in. diameter, over-all tolerances of $\pm 0{\cdot}004$ in. were readily obtained. In those very few cases where the uranium alloy required is not capable of being produced in a high-frequency vacuum furnace, the alternative process of arc melting using a consumable electrode is used. This process, however, suffers from the disadvantage that it produces only very simple shapes with a poor surface finish and requires the production of an electrode by some powder or other metallurgical process before casting can be carried out. In some cases, however, master alloys

Fig. 4 ***The stationary crucible, bottom-pouring, high-frequency vacuum furnace has proved highly efficient in producing uranium billets***

used for the high-frequency vacuum furnace have been made in the arc melting furnace. Where, because of structural properties, casting is not considered satisfactory for fuel-element manufacture, or where the lengths of bar or tube required render casting impossible, mechanical working must be employed.

All the methods commonly employed for engineering materials can be applied to uranium, but the only ones employed on any scale for fuel-element manufacture so far have been rolling and extrusion. Mechanical working is complicated by the anisotropic modifications of uranium. The hardness and resistance to deformation decrease uniformly with temperature in the alpha region and the ductility increases correspondingly up to the change-point from alpha to beta at 660°C. Rolling is usually carried out within the range 400–660°C and at these temperatures

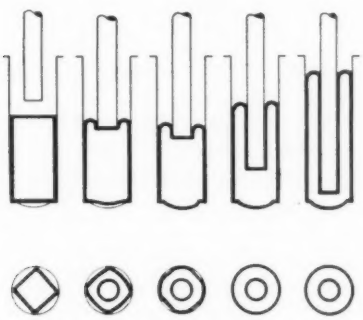
mechanical working produces a structure with a marked preferred orientation which will be referred to later. Conventional type steel rolling mills are satisfactory for producing uranium bar in this temperature range, round type rolls being preferable to the gothic and oval passes beloved of steel makers.

Uranium oxidises readily and round roll passes grip practically the whole circumferences, compact the oxide and prevent further oxidation. Moreover, by holding the whole of the material in compression they prevent tensile cracking which is frequent in gothic passes. The use of round rolls is not such a disadvantage with uranium because this metal tends to heat up tremendously during mechanical working, both as a result of its internal friction and friction with the rolls because of its high inertia. The beta phase is very brittle and attempts to roll cast material between 660° and 750°C results in disintegration without any appreciable deformation. Rolling is again possible above 750°C in the gamma phase, but at this temperature the resistance to deformation is so low that a long bar becomes almost impossible to handle as it falls directly from the roll on to the floor. Extrusion is usually carried out in this phase. The low resistance to deformation favours this process because of the necessity for keeping the loads on dies and containers to a reasonable limit and bending can be overcome by extruding vertically downwards.

The main difficulty with extrusion lies in the provision of suitable dies. Uranium alloys rapidly at temperatures of 735°C and over with metals of the iron, cobalt and nickel family from which most of the commercial metal-working tools are made. Something may be done by the use of graphite lubricants, and chrome plating and separation of die and container by means of a thick layer of graphite has been used very satisfactorily in France. Ideally, extrusion dies would be made of sintered or cemented carbides which are very hard and which do not alloy with uranium, but the rough handling they receive in most commercial extrusion shops usually results in premature failure during parting from the metal. The most satisfactory material for extrusion dies so far has been stellite. Stellite coatings can be readily laid down on steel and in spite of the cobalt content they are found satisfactory in practice, due probably to the extreme hardness of stellite which prevents deformation which may promote alloying.

As an illustration of the ease with which normal commercial processes can be applied to the fabrication of uranium, may be mentioned the case of push-bench drawing. This process which is applied to the manufacture of solid-drawn boiler and condenser tubes consists in taking a square billet and piercing it in a vertical piercing press as shown in Fig. 5. The billet, still hot, is then transferred to the end of a mandrel by which it is pushed through a series of plain or roller dies.

Uranium heated to 660°C was subjected to these processes, which are normally carried out on steel at 900°C, and perfect tubes as large as 6 in. diameter and 10 ft long and $\frac{3}{8}$ in. wall thickness were produced which were later reduced in diameter through a tube-reducing mill in the same factory. The protection of the oxide fuel in rolling and the speed with which extrusion can be carried out render the oxidation which occurs in these processes comparatively slight, but this does not apply during preheating except in those cases in which the heating can be carried out quickly by means of induction. For most of the experimental fabrication of uranium, heating was carried out inside a conventional furnace in an argon atmosphere in copper-lined steel containers which were used to transport the billet to the roll or press. Containers of this kind are, however, not convenient for high-speed production and satisfactory results have been achieved with a salt bath containing a eutectic mixture of lithium and potassium carbonate. The salt forms a protective film over the surface of the uranium and helps to protect it from atmosphere during the hot-working operation itself. A salt bath is particularly advantageous in the case of rolling, as it can be used at intermediate stages of the mechanical working



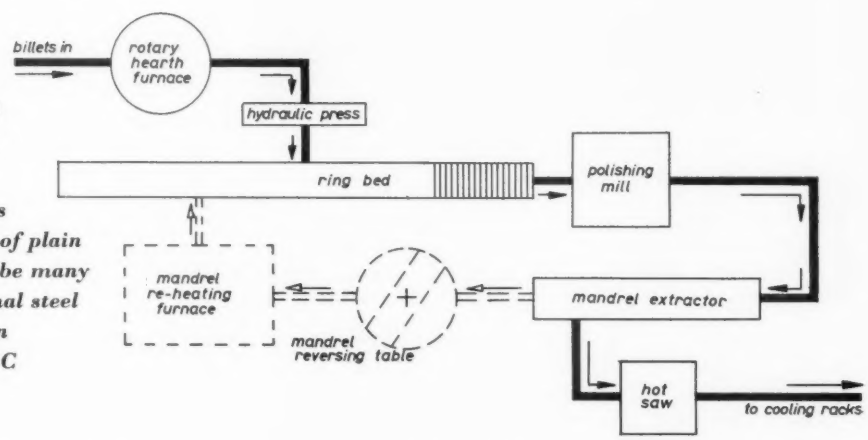


Fig. 5 *Square billets are pierced (above) and the bottles transferred to the ring bed (right)*

A mandrel then pushes them through a series of plain or roller dies into a tube many feet long. This is normal steel practice and is done on uranium at about 660°C

operation to regulate the temperature exactly, where, as we shall see later, such exact regulation is important for the metal structure.

The rolling operations so far described have been mainly concerned with the manufacture of bar. Where sheet or strip fuel elements are required, these can also be produced, although the greater ratio of surface to volume in sheet as compared with bar, render temperature control and the prevention of oxidation more difficult. Where very small thickness of strip or sheet is to be produced, it is often convenient to start operation by enclosing the uranium in a less readily oxidisable metal. If this material is nickel, then some means of preventing alloying of the uranium metal must be provided and this is usually done by means of a graphite film. After reduction to about 0·050 in. the uranium is removed from the protective metal and further reduced by cold rolling and annealing or by pack rolling. Special means of fabrication such as powder metallurgy, wire drawing, swaging and forging have been developed. Powder metallurgy has however been used to some extent in the manufacture of thorium bars because the softness, high ductility and favourable structure of this metal lend it to powder metallurgical methods of fabrication, whereas its high melting-point makes it difficult to cast.

Fuel-element damage

The methods and conditions of fabrication employed for uranium exert a great influence on its behaviour under neutron irradiation, and before considering more advanced methods of fuel-element manufacture and heat treatment it is necessary to examine the nature of these effects. They may be divided logically into two classes. Irradiation distortion, which takes place at comparatively low burn-up at relatively low temperatures, and fission-product damage, which occurs at higher temperatures and higher burn-up. All metals consist of an array of differently oriented crystals. The common cubic metals such as iron and aluminium exhibit a very high degree of symmetry and are described by means of three equivalent directions at right angles called by crystallographers the 100, 010 and 001 directions, which are related to the six crystal faces of a cube. The uranium crystal is also described by three mutually perpendicular axes, but it shows very great differences in properties in the three directions. This is illustrated by differences in the coefficients of expansion in these three directions, 18, — 2 and 28.

How crystals distort

If a crystal of uranium is subjected to neutron irradiation at 200°C it will distort so that the 010 direction increases in length by 100 per cent for a burn-up of one in a thousand atoms. The 100 direction will decrease in length by half and the 001 direction will not alter in length. This has been proved by a study of single crystals (Fig. 6*a*). If, now, a uranium specimen consisting of an aggregate of these crystals oriented in various directions is irradiated at 200°C, all the crystals composing it will attempt to grow in the 010 direction and contract in the 100 direction.

What happens to the crystals in the centre of such a mass is still a matter for discussion, but those on the surface will grow outwards when their 010 axes are normal and contract inwards when their 100 axes are normal to the surface. If a uranium specimen has a high proportion of its constituent crystals oriented so that the 010 axes are in a preferred direction, it will grow in that direction and contract in others. The roughening of the surface of coarse-grained random material is called wrinkling. The increase or decrease in length of oriented material is called growth. Cast uranium is of random orientation and large grain size and does not therefore change macroscopically in dimensions when irradiated, but wrinkles heavily (Fig. 6*b*). Fig. 7 shows the surface of a lead replica which has been made by pressing on to a wrinkled irradiated cast uranium bar. The only way of maintaining stable dimensions under these conditions is to produce a random array of very fine crystals (Fig. 6*c*).

The irradiation distortion described is very temperature-dependent. It has a maximum at 200°C and decreases with

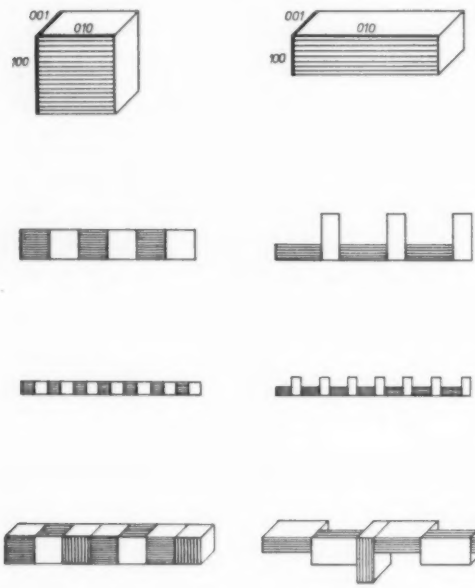


Fig. 6 *Uranium before* (left) *and after irradiation* (right)

a. A single crystal of uranium after neutron bombardment increases its 010 direction, shortens in the 100 direction, and remains unchanged in the 001 direction.

b. A coarse-grained random structure becomes increasingly wrinkled

c. A fine random structure remains comparatively smooth and stable

d. A structure with a high 010-preferred orientation increases in length. These are always fine grained

increase of temperature, reaching zero about 400°C. It also decreases as the temperature is decreased from 200°C till it reaches about a quarter of its maximum value at the temperature of liquid air.

At high temperatures irradiation has an even more serious effect. The uranium atom splits on fission into two or more atoms, which generally take the form of one atom of atomic weight about 80, and another of atomic weight about 140. These atoms can be shown to occupy a larger volume than the uranium from which they are formed and this would, other things being equal, result in a small increase in density with burn-up. Were these gases able to occupy their equilibrium volumes, it can be shown that one cubic centimeter of uranium would produce 4·73 cm^3 of stable inert gas at normal temperature and pressure for every 1 per cent burn-up. These gases are, however, produced in the lattice of the uranium crystal—usually at comparatively high temperature—and they are effectively insoluble. They can diffuse inside the uranium and should they reach a free surface they can diffuse out but, except when ionised, they are unable to get back. What normally happens, therefore, is that they diffuse until they reach a point at which they can form a nucleus. This results in the formation of a series of bubbles and at high temperatures this causes rapid increase in volume of the uranium.

Thermal cycling

These increases in volume can be calculated if the properties of the uranium are known, but in practice they are greater at low temperatures than would be expected from the calculations. This is probably due to effects on diffusion and uranium metal strength caused by anisotropy and cycling through the transformations. The high-temperature swelling is a problem whose solution is still in the development stage, but it could be reduced by the use of anisotropic uranium, free from phase-changes, with a creep strength as high as possible. The provision of uranium with this structure usually involves alloying additions which render it uneconomic for most normal power-producing reactors. Fortunately, however, uranium can be irradiated to reasonable burn-ups at low temperatures without having to take this phenomenon into account.

Uranium which will not grow

The techniques of stabilising uranium have so far, therefore, taken account mainly of low-temperature distortion. There are, in theory, two methods of producing stable fine-grained uranium: mechanical working and heat treatment. Uranium produced by working in the alpha-phase normally contains a high degree of preferred orientation. At low temperatures of working there is a strong tendency for the 010 direction to be oriented in the direction of working; such uranium will therefore grow rapidly in the direction of working under irradiation (Fig. 6*d*). At high working temperatures, just below the alpha-beta transformation, this 010 texture is replaced by a more complicated texture in which the 100 direction tends to dominate in the working direction; such uranium will decrease in length on irradiation. If working at a controlled rate is carried out at the correct temperature, it is therefore possible to find a mean at which the uranium neither grows nor contracts. It is, however, almost impossible to guarantee this in production, however carefully the temperature is held.

The second method of stabilising uranium against irradiation depends upon heat treatment. When uranium is cooled through the alpha-beta transformation, a random structure is produced as the beta structure recrystallises to alpha. The exact mechanism of the process is not fully understood, but it is known that, up to a point, the lower the temperature at which it occurs the finer the grain size, because the rate of formation of nuclei is large compared with the rate of alpha grain growth. The more rapid the cooling, the lower will this temperature be. For exceptionally pure uranium a very high rate of cooling, which can normally only be attained on fine wires, would be required and therefore fuel elements of the order of 1 in. diameter cannot be satisfactorily refined. The effect is really analogous to that of a carbon steel. If the

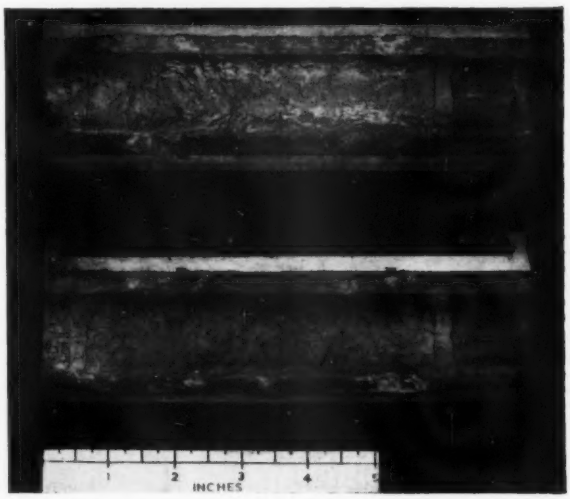


Fig. 7 ***Wrinkles on an irradiated cast uranium bar are reproduced by pressing on to lead***

steel metallurgist wishes to harden a component whose sections are too large for it to respond satisfactorily to straightforward quenching, he adds austenite-soluble material, such as nickel, which enables satisfactory hardening of steels to be carried out at much lower rates of quench. The whole phenomenon can be described by means of the familiar TTT curves.

A similar mechanism can be employed to grain-refine uranium, the most effective metal being chromium. Corresponding TTT diagrams can be drawn for uranium alloyed with this material and correct alloy compositions and quenching conditions produced for almost any purpose. One other point in which the heat treatment of uranium resembles that of steel is worth noting. During quenching, high internal stresses are set up which are released on heating or irradiation. If the material has not been quenched uniformly, so as to produce a symmetrical stress pattern, the fuel element might bow in the reactor with disastrous effect. Great care must therefore be taken during quenching.

Ceramic elements

The irradiation problem in a fuel element may be enormously reduced by replacement of the U^{238} by an isotropic material stable over the whole operating range. The most

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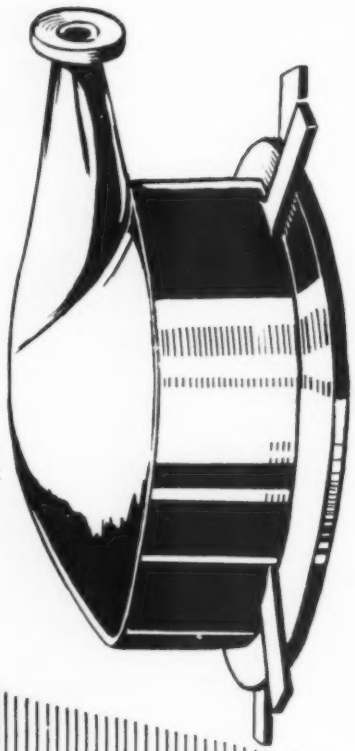

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advantageous material is thorium, which is cubic and free from phase changes below 1480°C. Alternatively, for certain research and special-purpose reactors the uranium may be diluted with aluminium or zirconium, or possibly steel. Oxides or carbides which are isotropic and retain their hardness at much higher temperatures than metals may be used instead. Although, because of its lower thermal conductivity, the centre temperature of oxide fuel elements will be higher, it is likely that the increases in volume and dimensional changes are likely to be less than for metals. On the other hand, such ceramics are very liable to fracture by thermal shock or possibly by the production of fission products, therefore no reliance should be placed on them as strength members, except against purely compressive stresses. Thus it is believed that thin sections only should be used and that adequate support must be provided by the can. The greater dispersion of the fissionable material involves increase in enrichment and conversion factor and this may well put up the fuel costs.

Ceramics may seldom be cast and forged, but must be made by powder metallurgy methods, cold pressed and sintered or hot pressed at very high temperatures. The most satisfactory hot pressing die material at these temperatures is graphite, which might contaminate oxide and lead to instability and undesirable coolant reactions. Cold pressing and sintering is therefore generally used. If the components are small, oxide is usually compressed in standard pelleting machines. Waxes or alcohols are used as binders, which are removed in the early stages of the sintering process.

Hydrostatic pressing

An extremely useful method and one which is coming into great favour is hydrostatic pressing. This process is admirably suitable for production of simple rods or tubes and the die costs are negligible. The material to be pressed is placed in a rubber tube inside a perforated steel tube, and the ends are closed. The assembly is then placed inside a hydraulic cylinder and a pressure of 20 tons per sq. in. applied. If a tube is required, the operation can be done on a mandrel, alternatively it can be done inside a tube and the pressure applied via the rubber internally. This process produces a much more uniform product as pressure is applied all over the compact, but larger dimensional tolerances must be allowed. Because of the high sintering temperatures, platinum or molybdenum wound furnaces must be used and atmospheres must be provided to prevent oxidation. Similar powder metallurgical processes may be used to make dispersed fuel elements of metal mixture or cermet type. In such cases the matrix is usually of the same material as the can to which it is bonded by rolling or extrusion.

Fig. 3 by courtesy of Dr Rogan and Mr White of Springfields factory

Mr. Wyatt's final article in this series first deals with some aspects of plutonium and the special precautions needed in handling this dangerous metal. It then describes in some detail the development of fuel rod cans and of rod and plate-type elements.

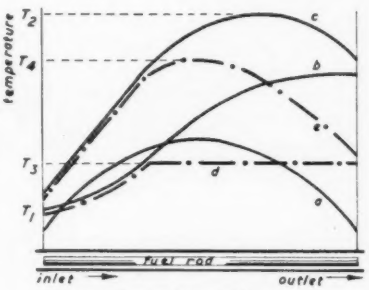
PATENTS

735,851 *Improvements in or relating to heat-transfer systems.* The United Kingdom Atomic Energy Authority (Inventor: Franz Eugen Simon) 31st August, 1955.

The use of a gas or liquid as a reactor coolant results in a thermodynamic inefficiency because the fluid takes up sensible heat over a range of temperatures. Heat, as latent heat, transferred to bulk liquid at constant temperature, as in a boiling reactor, results in ebullition and bubble formation, but if the heat-exchange medium is a mist or suspension of liquid droplets in a carrier gas it can be evaporated without these troubles and takes up heat at constant temperature. This is the basis of an invention for which an application was filed on 13th August, 1947.

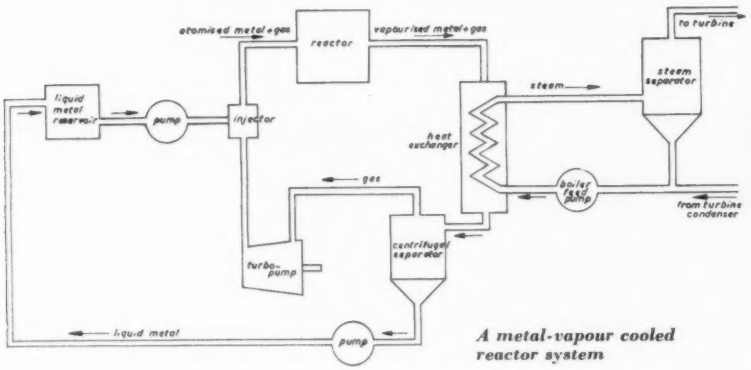
According to the invention, which is applicable to heterogeneous reactors, possible combinations of coolants might be, air carrying a mist of light or heavy water, while for higher-rated reactors sodium or potassium droplets in helium could be used. In the latter case the inventor claims that for a 100-MW heat reactor the rate of evaporation of sodium would only be about 20 kg a second. The relatively small quantity involved might, therefore, permit the use of substances which would be unacceptable in larger amounts.

The action of the vapour-cooled reactor may be followed by reference to the graph of heat release and temperatures along a typical fuel-rod channel in a heterogeneous reactor. In the case of a pure gas such as air or helium flowing through the channel, heat released in the rod is given on curve A and this results in gas temperatures B and rod temperatures C. If, however, a liquid suspension is included with the gas the coolant temperature will be given by curve D, the temperature rising



Heat exchange is mostly at T_3

from T_1 to T_3 (the boiling-point of the liquid) for a short distance and then remaining constant while the droplets are evaporated. With these conditions, the fuel-element temperatures should be given approximately by curve E, reaching a maximum of T_4 instead of T_2 with pure gas coolant. Maximum boiling temperatures of reactors are set by fuel-element considerations so that a reduction of the nature described should permit the attainment of higher power levels.



A metal-vapour cooled reactor system

754,551 *Improvements in or relating to apparatus for producing nuclear reactions.* Schlumberger Well Surveying Corporation, 3rd August, 1955.

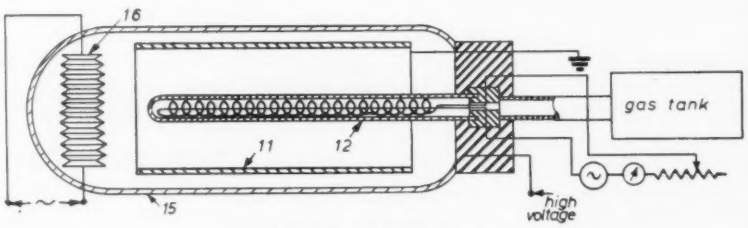
Compact neutron sources have considerable application in medicine and industry and in particular they are used for neutron logging in exploratory bore holes. The object of this invention is to provide a convenient particle accelerator suitable for this and other purposes.

Basically, it consists of a controlled source of gas ions, an accelerating potential, and a target area in which nuclear reactions can take place. One embodiment of the invention is shown in the diagram in which 12 is a heated tubular anode with very thin walls of palladium or platinum through which the heavier isotopes of hydrogen (deuterium or tritium) can diffuse when heated. The cathode, 11, is cylindrical, open at both ends and coated inside with a target material such as deuterium or tritium bound in zirconium or platinum. The whole assembly is maintained in a high vacuum inside the cylinder, 15.

Suppose hydrogen is supplied to the hollow anode. Enough heating is supplied to cause a slow radial leakage of deuterium through the anode wall. This is maintained at a positive potential of 20–100 kV with respect to the cathode and gas molecules diffusing are bombarded by electrons released from the cathode by cold emission. This produces deuterons which, on accelerating across the anode-cathode space, produce a D–T reaction in the tritium coating, resulting in a flow of high energy, mono energetic neutrons.

Not all the diffusing gas is ionised and un-ionised molecules will tend to spoil the vacuum, but if the anode is constructed in uranium or zirconium it will act as a getter and so tend to maintain the vacuum. If necessary, additional getters such as 16 may be included in the apparatus.

Several variants of the principle are included in the patent described in the specification.



A compact neutron source

These abstracts are made from British Patent Specifications with the permission of the Controller of Her Majesty's Stationery Office. Complete specifications may be obtained from the Patent Office (Sales Branch), 25 Southampton St, London, WC2, at 3s. a copy (including postage, inland and abroad).

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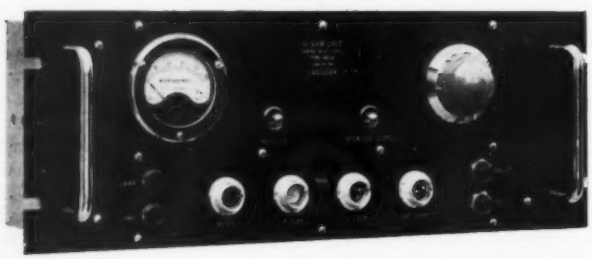

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COMPANIES

Richardsons Atomic

The well-known steam turbine firm, Richardsons, Westgarth and Co. Ltd, of Wallsend-on-Tyne, recently set up a separate company to conduct nuclear studies and developments. With a capital of £250,000, the new subsidiary is registered as Richardsons Westgarth Atomic Ltd, and has for its chairman Mr Harry Fothergill, the other directors being Mr O. J. Philipson and Mr J. R. Mackay.

The Company say they have formed a team of engineers, physicists and metallurgists for the design of nuclear reactors for both marine and land applications. The London Office is at 56 Victoria Street, SW1.

Sunvic Controls Ltd

In an advertisement on page xiii of our May issue, Messrs Sunvic Controls Ltd refer to an order received from the AEI John Thompson Group for the research reactor Merlin. We have been asked to point out that this order is for the complete control and display instrumentation.

Babcock output record

Net profits after tax for the year ended 31st December, 1955, of about £2·2m, compared with £1·9m for the previous year, were reported by Babcock & Wilcox Ltd chairman, W. Lionel Fraser, at the company meeting in London on 29th May. Mr Fraser referred to the acute shortage of skilled labour and of draughtsmen, and said it was gratifying that, in spite of this, the turnover had again reached a new high level. The firm, he went on, had been very active in nuclear energy work and as a result of its work at Calder Hall A, had obtained further contracts for Calder Hall B and Chapel Cross.

"Endewrance" high alloys

Dewrance & Co. Ltd, Great Dover St, London, SE1, the well-known makers of boiler mountings and piping valves, announce the formation of a Special Alloys Division to handle the firm's "Endewrance" high alloys. These alloys are particularly suited for components in industry where heat-, abrasion-, corrosion- and erosion-resistant qualities are necessary and can be supplied as machined and unmachined castings or in the form of welding rods. Full details, together with a copy of a new publication No. 682 describing these alloys, can be obtained from the above Division. This Division also handles the company's patent T.L.B. metal powder deposition process and powdered metals suitable for high-temperature brazing.

Dewrance are working in close collaboration with Coast Alloys Inc., Littleferry, New Jersey, for the development and sale of high alloy castings in this country, the Commonwealth and a number of European countries.

Matthew Hall for Calder B

A warning of more intense competition and rising costs was contained in chairman Bertram Baden's report to the Matthew Hall and Co. Ltd shareholders on 29th May in London. Mr Baden revealed that his company had installed £11m worth of equipment at British atomic establishments and factories, and added that the heavy mechanical work for Calder Hall A had advanced so well that the firm had obtained a similar contract for the B station. The Matthew Hall dividend was maintained at 30 per cent, less tax, on an increased capital.

Scots firm's valve orders

The Glenfield and Kennedy Group have received substantial orders from the AEA for valves for atomic plant, according to chairman H. Cowan-Douglas reporting to the Company meeting in Kilmarnock on 25th May. The Group trading profit showed some recession from the 1954 high, but the ordinary dividend was held at 20 per cent.

English Steel's plate for Calder

English Steel Forge and Engineering Corporation, Ltd, of Sheffield, are supplying, in all, some 4500 tons of 6-in. rolled plate for the Calder Hall and Annan power stations. It will form part of the thermal shields which protect the concrete radiation barrier against the heat effect of the reactor.

The first thermal shield, at Calder Hall, is already completed. Enclosing the reactor vessel, which is approximately 40 ft in diameter and 60 ft high, it takes the form of an octagonal wall 45 ft across and 80 ft high, with similar rolled plates forming the floor and roof.

Vertical columns made of 6-in. plate are also being supplied by the company. With the addition of thinner welded steel plates, these columns form the skeleton of the wall and hold in position the thermal shield plates. The thermal shield plates themselves are machined on their top and bottom edges to rest one on top of the other.

English Steel Forge and Engineering Corporation, Ltd, a wholly owned subsidiary of English Steel Corporation, Ltd, Sheffield, is also supplying certain portions of the Calder Hall and Annan reactor vessels themselves.

"Accelerate!"—Sir Claude Gibb

The year 1955 was a record one for C. A. Parsons and Co. Ltd. Addressing the 43rd Annual General Meeting of the company on 3rd May in Newcastle, chairman Sir Claude D. Gibb revealed that the net profit for the year was just under £2,000,000 after providing for taxation amounting to £1·7m.

Referring to the Nuclear Power Plant Company Ltd, of which Parsons are a member, Sir Claude said that it had grown in staff and strength and was now doing magnificent work in the research, development and design of nuclear power stations. He believed that the growing shortage of coal in Great Britain and the danger of relying upon oil from the Middle East as an auxiliary or alternative fuel would call for an acceleration of the programme. He assured shareholders that the Nuclear Power Plant Company and its eight member firms were ready to meet any increase in the British programme.

Atoms, Electrons and Industry

The Electronics Section of the Scientific Instrument Manufacturers' Association held an exhibition—*Atoms, Electrons and Industry*—in Bristol, from 6th to 8th June. Twenty-nine firms took part and showed by working demonstrations some recent developments of electronic and nucleonic instruments, and their application to a wide variety of industries. The AERE, Harwell, also cooperated.

INSTITUTIONS

Mining and metallurgy

On 22nd and 23rd March a symposium, organised by the Institution of Mining and Metallurgy, was held at the Royal Society of Arts, London. Twenty-two papers, of which ten were contributed by UKAEA staff, were presented on the extraction metallurgy of some of those less common metals which are currently assuming positions of great importance in world economy. Over 230 people attended, twelve countries being represented.

The Symposium was opened by the President of the Institution of Mining and Metallurgy, Mr Stanley Robson, who took the Chair for the first session. The Chairman of the other sessions were Professor C. W. Dannatt (Imperial College), Mr L. E. Djingheuzian (Dept of Mines and Technical Surveys, Ottawa) and Dr J. H. Watson (Royal Mint).

Six papers described processes applicable to several metals and included: chemical extraction applied to low-grade ores; solvent extraction; chlorination of complex tungsten, vanadium and chromium ores; oxide-chloride conversion processes and two overseas contributions—one on Canadian developments in niobium, tantalum, lithium, selenium and tellurium extraction, the other on selenium, tellurium and thallium extraction at La Oroya, Peru.

Uranium concentration by both physical and chemical processes from ores, the part played by anion exchange in uranium recovery from leach solutions and the pilot plant concentration of Mindola ore were the subjects for three papers on uranium; a fourth dealt with the magnesium reduction of uranium tetrafluoride to metal, the last stage in the processing of uranium ore to metal.

The processes for the production of vanadium metal described in two papers were, as for uranium, supplemented by a paper outlining the physical processes used at a mine (Abenab) to concentrate vanadium minerals from ores. Various routes to the production of niobium metal, including chlorination and the distillation of volatile chlorides, were discussed in three papers. A further group dealt with the production of beryllium metal at Milford Haven, the fluoride route to the metal and the use of stable halide vapours in the purification of beryllium and titanium. The final session discussed the extraction of thorium from monazite, titanium extraction by fused-salt electrolysis and the preparation of hafnium-free zirconium.

It is expected that a special volume covering the whole of the proceedings of the Symposium, together with the papers, will be published at about the end of this year.

Photocopying services

The Fédération Internationale de Documentation has recently published a revised edition of the *Directory of photocopying and microcopying services*, price Fl. 6 (12*s*.).

New features include: the texts of the British and US fair copying declarations; details of the Unesco Coupon scheme, including addresses of distributing bodies; and recommendations of the International Organisation for Standardisation regarding sizes of microcopies, etc.

The *Directory* can be obtained from the Fédération Internationale de Documentation, Willem Witsenplain 6, The Hague, Netherlands.

Radioactive poisoning

Measurement of the normal body burden of radioactive material was one of the subjects discussed at a recent conference at Leeds University. The normal body burden is mostly due to K^{40}. Since naturally occurring potassium, of which 0·112 per cent is the radioactive isotope K^{40}, constitutes 0·25 per cent of the lean body weight, a 70-kg man contains about 135 grams of potassium and consequently about 10^{-8} curie of gamma-activity.

Measurements of this type have been made over a period of several years, but recently measurements have been made with novel apparatus comprising scintillation counter equipment in association with pulse-amplitude analysers, which allow identification of the nuclides present as well as an activity determination. At the Leeds Conference it was disclosed that measurements made both in America (at the Argonne National Laboratory) and in this country (at Harwell) had revealed that all persons tested had contained about the expected amount of K^{40}, and in addition a small amount of Cs^{137}. This caesum isotope is produced in fission, and it could be that the Cs^{137} is from radioactive "fall-out" from weapon trials. The amount found was very minute, about 4×10^{-9} curie, but is nevertheless significant. The maximum permissible body burden as laid down by the ICRP is 90 microcuries, or 2500 times this amount. It may be wondered, if the Cs^{137} really originates from "fall-out", why this isotope and apparently none of the other fission products have been found. A reason can be advanced —it is that the human body selectively absorbs caesum and essentially enhances its abundance by a very large factor. However, whilst the sensitive body monitors now in use at the Argonne and at Harwell have not so far revealed the existence of minute quantities of other materials, it is understood that surprising results have been obtained by subjecting dirt from domestic vacuum cleaners from ordinary houses to gamma-ray spectrometer analysis. Activities of the order of 10^{-8} curie have been measured and identified as Ce^{141}, Ru^{106}—Rh^{106}, and Zr^{95}—Nb^{95}.

Protection too high?

The United Kingdom Atomic Energy Authority spend about £50 a year on every employee in maintaining standards of health protection according to Dr A. S. McLean, principal medical officer of the Industrial Group.

Dr McLean was addressing the annual meeting of the Royal Society for the Promotion of Health at their Blackpool meeting on 26th April and he claimed that as a result of these measures "no single case of radiation sickness has yet been observed in the British atomic industry, nor any new disease". Other speakers in the session devoted to nuclear radiation protection included Dr H. G. Dunster from Harwell and Dr A. R. W. Wilson, an Australian delegate, who spoke of "the unrealistically high standard of the maximum permissible level of radiation".

Long-term genetic effects occupied a good deal of the Conference's time and delegates heard M Candeau, Director-General of the World Health

Organisation, who pointed out that there were considerable morphological and functional differences between experimental animals and men. It was therefore of the greatest importance to obtain some direct findings on the effect of irradiation by inheritance on man himself.

Metallurgy must set pace

The discussion on 11th April organised by the Nuclear Energy Committee of the Institute of Metals, heralded a welcome dissemination of knowledge on this very important branch of the industry.

Three papers by UKAEA members were discussed and the introduction of these by Dr Ivor Jenkins cogently demonstrated the vital role which metallurgy has played in the past and emphasised that the future progress waits upon the development of materials for the new types of service. In discussion, Dr S. G. Bauer urged that it should be recognised that initiative lay with the metallurgist, and that specifications for new reactors should depend primarily on what the metallurgist considered possible. The nuclear and engineering design would then follow the principles set out; at present the order of design tends to be the reverse of this.

Mr L. M. Wyatt gave a brief account of the early metallurgical considerations at Harwell on the design of the Calder Hall reactor and showed how the choice of carbon dioxide for cooling and magnesium for canning had been made.

The large attendance at the meeting was an indication of the desire of metallurgists to become acquainted with this branch of their science. It was clear that the organisation of discussions of this kind are very necessary and will do very much to breed a healthy interest in the subject of which too little is known by metallurgists outside the Authority.

Surface activity

The first International Congress of Surface Activity was held in Paris in 1954: the second will be held in London from 8th to 12th April, 1957, with Lord Brabazon of Tara as President of Honour and Professor Sir Eric Rideal as President.

An organising committee has been set up under the chairmanship of Dr Leslie H. Lampitt and with Sir Charles Dodds as Honorary Treasurer and Lt-Colonel Francis J. Griffin as Honorary Secretary.

Membership of the Congress is open to all interested persons on payment of the membership fee of £4. It is hoped to issue a detailed programme in the near future—enquiries to: The Honorary Secretary, 2nd International Congress of Surface Activity, 14, Belgrave Square, London, SW1.

Bibliography on mechanisms

A new international bibliography entitled *Mechanisms* has been announced. This will list papers, articles and books which appear on relevant subjects in the literature of the major industrial countries. Electrical, electronic, hydraulic and pneumatic devices will be covered, as well as purely mechanical devices. There will be two pages of comment and notes, and it is hoped to include illustrations, with news of patents, editorials and original articles. The bibliography will be classified by subject with an annual name index and possibly a subject index. It will be issued monthly and the subscription will be £1 1*s*. (25*s*. for overseas subscribers). Enquiries to P. Grodzinski, 41 Tudor Close, Belsize Avenue, London, NW3.

NAMES IN THE NEWS

Rear Admiral Sir Edward Rebbeck, KBE, CB, has been appointed an additional member of the board of directors of Vickers Nuclear Engineering Ltd. Admiral Rebbeck retired from the Royal Navy last October and now heads the Vickers group which is working on nuclear energy for marine propulsion.

General Sir Ronald W. Mathews, JP, DL, M Inst T, recently announced his retirement as chairman of the Brush Group Ltd. Up to Sir Ronald's place steps **Mr G. C. R. Eley, CBE,** who has been the Brush deputy chairman since 1953. Mr Eley is a director of the Bank of England and a director of several other private firms.

The Hon J. K. Weir has relinquished his joint managing directorship of G. & J. Weir Ltd, Glasgow, to devote himself full time to the chairmanship of the Weir Group. **Mr J. A. Russell Lang** succeeds him as sole managing director.

Mr M. H. L. Lewis has been appointed a director of Crompton Parkinson Ltd, and **Mr Michael Parkinson** has been appointed an executive director.

Mr R. Keir Watson has been appointed an executive director of the Plessey Company Ltd, Ilford, Essex.

Mr J. G. Boddy has been appointed manager of the turbine contracts department of the British Thomson-Houston Company, Rugby.

Mr E. S. Jackson is the first holder of the new post of Director-General, Atomic Weapons, Ministry of Supply, following the retirement of Lieutenant-General Sir Frederick Morgan as Controller of Atomic Weapons.

Sir Patrick Hamilton, Bart, has been made chairman of the Expanded Metal Company Ltd, London.

Professor E. C. Rollason goes to Birmingham University in September to the Chair of Industrial Metallurgy. Professor Rollason is at present the Henry Bell Wortley Professor of Metallurgy at Liverpool University.

Sir Bernard Keen and **Mr A. G. P. Powell** have been appointed directors of Baird & Tatlock (London) Ltd.

Mr Donald Goulding has been appointed head of the export sales department of Winston Electronics Ltd, Shepperton, Middx.

Mr G. A. G. Ive has been appointed managing director of Radiovisor Parent Ltd, in succession to the late Mr E. Harley Bell.

Mr Kurt Deutsch has been appointed design engineer, titanium plant, ICI Metals Division, Witton, Birmingham.

Mr R. C. McCleod has been released at his own request from the position of Chief Engineer, Turbine Division, the Brush Electrical Engineering Company Ltd. Mr McCloud remains in charge of axial-flow turbines, responsible to the technical director.

Sir Harry Jephcott has been appointed chairman of the advisory council of the Department of Scientific and Industrial Research. He succeeds **Sir Hugh Beaver,** who expressed a wish to relinquish the chairmanship, but who will continue to serve on the council.

Viscount Chandos has been re-elected President of the British Electrical Development Association.

The Hon. Geoffrey Cunliffe has been elected president of the Aluminium Development Association with **Mr Spence Sanders** as vice-president and **Mr J. H. Mayes** chairman of the executive committee.

RESEARCH REPORTS

Harwell

*The following reports have recently been made available to the public by the Atomic Energy Research Establishment, Harwell. They may be borrowed or photocopies obtained from the following libraries: British Museum; University Library, Cambridge; Radcliffe Science Library, Oxford; National Library of Scotland, Edinburgh; Patent Office Library, London; Science Museum Library, London; Mitchell Library, Glasgow, and the Central Libraries at Birmingham, Liverpool, Manchester, Newcastle-upon-Tyne and Sheffield. Reports marked * may be purchased from Her Majesty's Stationery Office.*

AERE C/M 262 **Fission product gases from a homogeneous power reactor.** *P. C. Davidge, C. J. L. Lock.* (*Nov.* 1955. 17 *pp.*) 3*s.**

AERE GP/M 153 **X-ray diffraction examination of CaF_2 slag (Springfields).** *J. Adam.* (*June* 1953. 7 *pp.*)

AERE I/M 39 **The separation of Mn^{54}, Co^{56}, Co^{58}, Zn^{65} and Nb^{95m} in a carrier-free state by the use of anion exchange resin.** *C. E. Mellish.* (*Dec.* 1955. 4 *pp.*)

AERE N/R 134 **The measurement of the Laplacian in a lattice of uranium metal rods and graphite.** *D. V. Booker, W. S. Eastwood, F. W. Fenning, T. M. Fry, E. R. Wiblin.* (*Oct.* 1947, 26 *pp.*)

AERE I/R 1688 **Prompt gamma-rays from neutron capture as a means of oil well control.** *D. B. Smith, G. R. Church.* (*Oct.* 1955. 12 *pp.*)

AERE EL/R 1753 **The rapid detection and continuous monitoring of radio-active contamination on dust in laboratory air.** *K. E. G. Perry.* (*Sept.* 1955. 65 *pp.*)

AERE T/R 1791 **Scattering of polarised nucleons by nuclei.** *F. C. Barker.* (*Nov.* 1955. 25 *pp.*)

AERE T/R 1792 **The wriggling discharge in free space.** *S. J. Roberts and others.* (*Nov.* 1955. 33 *pp.*)

AERE GP/R 1800 **An experiment study of the S-band multitron.** *K. Dolder.* (*Dec.* 1955. 29 *pp.*)

AERE C/R 1805 **The determination of niobium and molybdenum in uranium ternary alloys.** *G. W. C. Milner, G. A. Barnett, A. Bacon.* (*Dec.* 1955. 15 *pp.*) 2*s.* 6*d.**

AERE M/R 1854 **X-ray diffraction studies of "active" magnesium.** *D. K. Thomas, T. W. Baker.* (*Jan.* 1956. 10 *pp.*)

AERE C/R 1861 **The temperature distribution in a heated clay block and its application to the problem of fission product disposal.** *C. B. Amphlett, D. T. Warren.* (*Feb.* 1956. 9 *pp.*)

AERE NP/L 1 **Lectures on the theory of neutron scattering.** *D. M. Brink.* (*Feb.* 1956. 19 *pp.*)

Chalk River

The following reports are published by Atomic Energy of Canada, and may be obtained from: Scientific Document Distribution Office, Atomic Energy of Canada Limited, Chalk River, Ontario. Remittances should accompany the order and should be in the form of cash, bank or express postal money orders or cheques made payable in Canadian funds at par in Chalk River to Atomic Energy of Canada Limited.

AECL 10 LT-35 **Theory of nuclear magnetic moments.** *A. K. Kerman.* (1952. 33 *pp.*) 50*c.*

AECL 24 CRT-526 **Coulomb functions for large values of the parameter.** *T. D. Newton.* (1952. 10 *pp.*) 25*c.*

AECL 62 CRP-292 **Proportional neutron counters.** *B. H. Flowers.* (1946. 17 *pp.*) 25*c.*

AECL 63 MT-220 **Thermal utilization in a system containing two moderators.** *E. A. Guggenheim.* (1946. 10 *pp.*) 25*c.*

AECL 78 LE-36 **The determination of radon concentrations in air.** *G. Cowper, S. D. Simpson.* (1953. 7 *pp.*) 25*c.*

AECL 82 CRR-548A **Report on atomic power symposium held at Chalk River, Ontario, on 9th, 10th and 11th of September, 1953,** *W. J. Henderson, Ed.* (202 *pp.*) $2.

AECL 96 PR-P-20-E **Progress report—electronics branch—October 1 to December 31, 1953.** *J. Hardwick.* (12 *pp.*) 25*c.*

AECL 104 PR-P-21-E **Progress report—electronics branch—January 1 to March 31, 1954.** *J. Hardwick.* (18 *pp.*) 25*c.*

AECL 106 CRT-569 **Tables of X coefficients.** *J. M. Kennedy, B. J. Sears, W. T. Sharp.* (1954. 26 *pp.*) $1.

AECL 108 IM-6 **Operating and technical manual: general purpose counting-rate meter AEP 1902A.** *R. J. Cox.* (1950, rev. 1954. 33 *pp.*) 50*c.*

AECL 111 MTec-143 **Heat transfer experiments with special reference to the thermal resistance of anodized layers.** *S. G. Bauer, P. M. Milner.* (1945. 15 *pp.*) 25*c.*

AECL 127 PR-P-22-E **Progress report—electronics branch—April 1 to June 30, 1954.** *J. Hardwick.* (22 *pp.*) 50*c.*

AECL 130 CR-HP-577 **The annular impactor.** *G. W. C. Tait.* (1955. 12 *pp.*) 25*c.*

AECL 131 DL-15 **Canadian power development—future possibilities.** *W. B. Lewis.* (1954. 18 *pp.*) 25*c.*

AECL 137 CRT-566 **Neutron density in an infinite, non-capturing medium surrounding a long cylindrical body which scatters and captures neutrons.** *S. A. Kushneriuk, C. McKay.* (1954. 75 *pp.*) $1.

AECL 139 CRT-580 **Statistical factors for electromagnetic transitions.** *J. M. Kennedy, W. T. Sharp.* (1954. 27 *pp.*) 50*c.*

AECL 146 PDB-95 **A bibliography of mass spectrometry references.** (1955. 167 *pp.*). $1.50.

AECL 157 CRP-584 **The elastic scattering of charged particles by nuclei.** *A. J. Ferguson.* (1954. 47 *pp.*) 75*c.*

AECL 160 CRP-287 **Experimental determination of the effectiveness of control rods in a pile.** *C. N. Watson-Munro.* (1946. 10 *pp.*) 25*c.*

AECL 163 CRE-374 **The production of heavy water at Trail, B.C.** *E. A. Barlow.* (1948. 16 *pp.*) 25*c.*

AECL 165 DL-16 **Economic aspects of nuclear power.** *W. B. Lewis.* (1955. 9 *pp.*) 25*c.*

AECL 174 PR-P-25-E **Progress report—electronics branch—January 1 to March 31, 1955.** *J. Hardwick.* (18 *pp.*) 25*c.*

AECL 178 DL-17 **Possibilities of generating atomic electric power at competitive rates.** *W. B. Lewis.* (1955. 23 *pp.*) 50*c.*

AECL 180 DL-18 **Atomic energy a source of future power.** *W. B. Lewis.* (1955. 10 *pp.*) 25*c.*

AECL 186 DR-18 **An atomic power proposal.** *W. B. Lewis* (1951. 14 *pp.*) 25*c.*

AECL 187 DR-21 **Reactivity changes expected and observed in long irradiation of natural uranium in the NRX reactor.** *W. B. Lewis.* (1952. 40 *pp.*) 50*c.*

AECL 188 DR-28 **Calculated reactivity changes in the long irradiation of natural uranium.** *W. B. Lewis.* (1953. 15 *pp.*) 25*c.*

INTRODUCTION

Zirconium (Zr) has a high melting-point, excellent corrosion resistance and a low absorption cross-section for therm and is therefore of interest as a canning and structural material in nuclear reactors. Zirconium is the ninth metal in a the earth's crust, being present in greater quantities than nickel, copper, zinc and lead. The most important sour —zirconium silicate ($ZrSiO_4$).

Two methods are currently used to produce high-purity zirconium: 1. The van Arkel, or iodide, process; 2. The K Since the first method requires the use of metallic zirconium made by other processes, the end-product is prohibitive for most commercial purposes, and the Kroll process is generally used for large-scale production. Zirconium, as normal contains up to 3 per cent of hafnium which, from the nuclear point of view, is undesirable because of its very high cross-section. Apart from this, the hafnium appears to exert little influence on the other properties of zirconium. In t ture of reactor-grade zirconium, the chemical separation of hafnium is introduced as an additional step in the product

PHYSICAL PROPERTIES

atomic number: 40 **atomic weight:** 91·22 (chemical), 91·24 (physical) **packing fraction:** — ($\times 10^{-4}$ **absorption +-section (thermal):** 0·18 barns **density at 20°C:** 6·49 ± 0·001 g/cm³ **melt** 1845°C **boiling-point:** 3577°C **allotropic transition:** alpha stable from room temp. to 863 ± stable from here to melting-point.

thermal expansion *(hafnium-free, annealed at 1000°C)*

temp. °C.	*linear coeff. of expn.*	*temp. °C.*	*linear coeff. of expn.*
— 183	5·66 × 10^{-6}/°C	538	6·10 × 10^{-6}/°C
— 70	5·88 ,,	760	5·97 ,,
204	6·23 ,,	871	5·76 ,,
316	6·23 ,,		

expansion along the he is reported to be abou along the basal axial dir

thermal conductivity: 0·040 cal/cm/cm²/sec/°C at 25°C **specific heat:** 0·0659 cal/g/°C at 25°C

ELECTRICAL PROPERTIES

volume conductivity: 4·1 per cent of the International Annealed Copper Standard at 20°C
specific resistance: 39·84 microhm/cm³ at 0°C for pure, degassed, annealed metal
temperature coefficient of resistivity: 44·0 (± 1·0) × 10^{-4}/°C from 0°C to 200°C
pressure coefficient of resistivity: $\frac{\Delta R}{R_0} = -0{\cdot}39 \times 10^{-6}p + 5{\cdot}5 \times 10^{-12}p^2$ at 250°C (p in kg/cm²)

MECHANICAL PROPERTIES

The mechanical properties of unalloyed zirconium are particularly sensitive to the prior history and the purity o particularly with respect to oxygen and hydrogen.

elasticity of annealed, or as-deposited, iodide zirconium

modulus of elasticity: 11·3 (± 2·3) × 10^6 lb/in². **shear modulus:** 4·76 × 10^6 lb/in².
Poisson's ratio: 0·35 **longitudinal wave velocity:** Kroll; 4·62 × 10^5 cm/sec. Iodide; 4·65 × 10^5 c

short time tensile (arc-melted iodide zirconium)

temperature °C	*strength, ton/in²*		*elongation in 2 inches, %*	*reduct ar %*
	yield (0·2%)	*ultimate*		
room	4·4	15·5	47	4
150	3·75	10·3	53	6
260	2·5	8·2	57	6
315	2·7	8·0	52	5

ion for thermal neutrons,
nth metal in abundance in
mportant source is zircon

cess; 2. The Kroll process.
is prohibitively expensive
um, as normally prepared,
f its very high absorption
irconium. In the manufac-
in the production scheme.

action: — (6·5 ± 0·9)
g/cm³ **melting-point:**
. to 863 ± 3°C ; beta

along the hexagonal axis
d to be about twice that
basal axial directions.

t 25°C

0°C

n kg/cm²)

d the purity of the metal,

4·65 × 10⁵ cm/sec.

	reduction in area %
	46
	63
	65
	57

tensile and hardness at room temperature [1]

	Kroll (0·11% O_2)		iodide (0·04 to 0·06% O_2)	
	50% cold worked	annealed 705°C	hard drawn	annealed 790°C
ultimate tensile, ton/in²	36·9	21·9	37·2	16·0
proof, (0·2%), ton/in²	33·7	13·0	31·1	7·1
prop. limit, (0·1%), ton/in²	18·7	7·5	14·3	3·7
elongation, %	not reported	not reported	18·0	31·0
hardness, (Rockwell)	B-95	B-83	B-87·4	B-30·0

hot hardness (arc-melted) [2]

temp. °C	hardness V.P.H.		temp. °C	hardness V.P.H.	
	Kroll	iodide		Kroll	iodide
room	180	145	500	38	78
100	132	137	600	30	65
200	105	123	700	22	42
300	86	102	800	13	23
400	80	88			

creep (arc-melted, iodide)

temp. °C	creep rate in./in./hr	stress lb/in.²
399	10^{-6}	2 500
316	10^{-6}	9 500
260	10^{-6}	12 500
399	10^{-4}	7 000
316	10^{-4}	12 000
260	10^{-4}	14 000
399	10^{-2}	11 000
316	10^{-2}	13 500
260	10^{-2}	15 500

impact (arc-melted, iodide, furnace-cooled from 705°C)

temp. °C	energy absorbed ft-lb	
	9 ppm H_2	31 ppm H_2
— 180	48	—
— 80	50	—
0	52	—
20	—	8
100	63	15
150	—	36
200	102	—
250	—	95
300	87	100
350	—	98

fatigue (arc-melted, iodide)

temp. °C	endurance limit lb/in²	
	notched	unnotched
room	8 000	21 000
400	6 500	10 500

compression (iodide)

$$-\frac{\Delta V}{V} = 10{\cdot}97 \times 10^{-7}p - 7{\cdot}44 \times 10^{-12}p^2 \text{ at } 30\,^{\circ}C$$

$$-\frac{\Delta V}{V} = 11{\cdot}06 \times 10^{-7}p - 7{\cdot}80 \times 10^{-12}p^2 \text{ at } 70\,^{\circ}C$$

p in kg/cm². Applies up to 12 000 kg/cm²

Zircaloy—II The use of zirconium in pressurised-water reactors has resulted in the development of a corrosion-resistant alloy—Zircaloy II—in the USA. This combines good corrosion resistance, low neutron absorption and improved mechanical strength.

chemical composition (wt. %)

1·2–1·7 Sn: 0·07–0·20 Fe: 0·05–0·15 Cr: 0·03–0·08 Ni: 0·010 (max.) N_2: 0·008 (av.) N_2: 0·17 (av.) O_2.

tensile strength

temp. °C	tensile, ton/in²		reduction in area %	elongation in 2 in., %
	yield (0·2%)	ultimate		
room	20·0	30·6	36	22
260	8·2	14·2	58	36
480	4·7	9·9	58	36

modulus of elasticity: 13·8 × 10⁶ lb/in²

V-notch Charpy impact strength at room temperature:
6 ft–lb (aged)
55 ft–lb (quenched)

high-temperature water corrosion

290°C **Water:** $w = 0{\cdot}50t^{0{\cdot}30}$
315°C **Water:** $w = 0{\cdot}74t^{0{\cdot}26}$
360°C **Water:** $w = 0{\cdot}76t^{0{\cdot}38}$ (up to **112** days)
400°C **Steam** (**1500** lb/in.²)**:** $w = 1{\cdot}10t^{0{\cdot}32}$ (up to **41** days)

w = weight gain, mg/dm²
t = time in days

references

general: Zirconium *by G. L. Miller London: Butterworths*
Metallurgy of Zirconium: *by B. Lustman and F. Kerze New York: McGraw-Hill*
(1) *E. T. Hayes and W. W. Stephens.* Metal Progress: *1953, 63, 97*
(2) *R. C. Burnett. AERE M/M 98 (to be published)*

DATA SHEET 2

zirconium and zircaloy II
mechanical properties

Nuclear Power
The journal of British nuclear engineering

JUNE 1956

BOOKS

Reactor Handbook—Engineering *Prepared by the U.S. Atomic Energy Commission. 8 in. by 10 in. 1088 pp. New York: McGraw-Hill. Price 112s. 6d.*

This book of over 1000 pages is divided into eight sections. These are concerned with solid-fuel systems cooled by water, by liquid metal and by a gas, and with fluid-fuel systems where the carrier is water, a liquid metal or a fused salt. The two final sections are devoted to handling and control, and to data on various reactor designs. Each section is divided into a number of chapters written by different authors, all of whom are actively engaged in various atomic energy projects. It is quite clear that all these authors know their job but were not given too much time to write about it, and that the editors have succeeded in avoiding overlapping but have not quite succeeded in achieving integration.

These blemishes are trivial when viewed against the background of the enormous amount of information which the book contains. Almost every section includes tables or curves giving the results of original experiments, and this mass of data is available nowhere else. However, it must be noted that the cut-off date is hardly ever later than January 1953, so that where the information given leaves something to be desired, more recent data should be sought in the papers published at Geneva.

In the section dealing with water-cooled reactors the chapters on water decomposition under radiation and on corrosion contain a mass of valuable data. The chapter on the spatial distribution of heat generation is well written and deals with an important subject on which little has been published. On the other hand, boiling-water reactors and boiling phenomena in water reactors are hardly mentioned.

The section on liquid-metal cooled systems has good chapters on handling problems and on mechanical components and design consideration.

The section on gas-cooled systems contains little of interest. The section on aqueous-fuel systems contains a mass of information on reactor theory, on the properties of various solution and slurry systems and on nuclear and engineering design. The sections on liquid-metal fuel and on fused-salt systems are shorter but quite adequate. The section on handling contains a great deal of valuable factual information. Every engineer working in the reactor field must know his way about this massive book.

B. L. Goodlet

Reactor Handbook—Materials *Prepared by the U.S. Atomic Energy Commission. 8 in. by 10 in. 614 pp. New York: McGraw-Hill. Price 79s.*

The Reactor Handbook represents, to the engineer or scientist denied access to the classified literature, one of the first fruits of the Geneva Conference. Thus it is to be welcomed as evidence of the intention of one nation that has made major advances in nuclear engineering to disseminate its knowledge widely.

This volume is intended to provide a handbook on those materials which are potentially suitable for use as fuels or structural materials in thermal or fast reactors. The opening chapter outlines the functions required; succeeding chapters cover the principal categories of materials. Metals of major importance, with their alloys, are dealt with in separate chapters, as are carbides, cements and concretes, graphite, hydrides and high cross-section materials. Beryllium oxide and carbide and silicon carbide are also treated separately, but other items are treated very scantily, e.g. oxides and carbides of uranium and plutonium, cermets. Information on zirconium is restricted, niobium and tantalum are not specifically dealt with.

For each material, information is to a standard schedule, covering topics ranging from Abundance, through Extraction and the various properties, to the divers fabrication techniques. Use of the book for reference is eased by this standard format, coupled with alphabetic presentation and a comprehensive index. Much of the data is summarised in well-conceived diagrams.

Reactor engineering requirements impose such unusual restrictions on materials used that a volume of this kind can embrace more pertinent information than a multiplicity of normal works of reference. This advantage is partly offset by three factors; firstly, the material is only complete to 1952; secondly, the published version has been prepared by simply deleting all classified information from the more comprehensive volume used by the USAEC; thirdly, as the preface expressly states, the volume was originally produced to a time schedule which allowed little opportunity for correlation between sections. The use of many specialists of repute promoted accuracy at the time of preparation, but individual differences of judgment occasionally intrude.

The book will form a useful reference for those are are mindful of its limitations, but may tempt the unwary to use outmoded information because it is so accessible. One notable example is the uranium-titanium constitutional diagram, now superseded by one that is radically different.

It is to be hoped that the interest aroused by the Handbook will stimulate the production of a more comprehensive edition, retaining the same mode of presentation and capable of being used with confidence by all interested in Reactor Technology.

M. B. Waldron

Law and the Engineer *by C. F. Mayson. 1953. 6 in. by 9 in., 470 + xx pp. London: Chapman and Hall Ltd. Price 63s.*

It was almost certainly a solicitor who first said, ***The man who is his own lawyer has a fool for his client***; but there is a good deal of truth in the aphorism for all that. Nevertheless, it can do no harm for the layman to know what may be called the elements of legal hygiene; the engineer in particular is brought into contact with many aspects of the law in his daily work.

Mr Mayson, who is both a barrister and an electrical engineer, has written a most attractive and effective book, which should be of value not only to the engineer but also to the works or commercial manager. Its standing on the legal side is sufficiently guaranteed by the fact that Lord Justice Denning has written a foreword.

The book deals first with the English legal system, with chapters on the scope and machinery of the Civil Law, Evidence and Documents. The second part deals with the Law of Contract in 14 chapters, including Agency, Hire-

continued on page 96

McGraw-Hill

NATIONAL NUCLEAR ENERGY SERIES

The National Nuclear Energy Series is a record of the research work done under the Manhattan Project and later under the Atomic Energy Commission. Twenty-seven titles are now in print, covering varied scientific and technical developments. The list below is a selection from these titles

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Division II	**16**	**Engineering Developments in the Gaseous Diffusion Process** *Benedict and Williams 1949*	15s
Division III	**1B**	**Theory of Isotope Separation** *Cohen and Murphy 1951*	19s
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The layout is that of a scientific and not that of a legal textbook—a minor point, but one which will help the reader to feel at home. The style is easy and clear, and the cases selected for discussion have been chosen as far as possible from those with an industrial context. The book is up to date, a most important point, for many of the branches of the law are changing at what the scientist would regard as breakneck speed. The text is correct up the end of 1954, and a page at the front notes changes up to May 1955.

This book can be most strongly recommended for the library of any manufacturing firm, whether or not it possesses a special legal department. *M. H. M. Arnold*

Engineering Dynamics, vol. III—Steam Turbines *by C. B. Biezeno and R. Grammel. 10·25 in. by 7·5 in., 276 pp. Glasgow: Blackie & Son Ltd. Price 45s.*

This is volume III of a series which has already covered the theory of elasticity (vol. I) and elastic problems of single machine elements (vol. II). A fourth volume is to cover internal-combustion engines. About half of the present volume is devoted to stresses and vibrations of discs, with about a quarter each to stresses and vibrations of blades; stresses and critical speeds of shafts and rotors. The space given to discs may seem rather unbalanced in view of the tendency of some steam-turbine builders to do without them, but it will interest those concerned with smaller gas turbines. All the subject-matter is mathematical; in fact the book may be regarded as a series of selected examples of mathematics applied to certain turbine problems, none of which is specific to steam turbines. It will therefore be useful to those who are expected to use mathematics in stress and vibration studies—particularly in the gas-turbine industry where weight is important and factors of safety can be low. It should be made clear that it is not a comprehensive book either on vibrations or on steam turbines and does not attempt to replace such a classic as Stodola's *Steam and Gas Turbines*, which in the fifth edition quoted by the authors deals with a wider range of problems even on vibrations while supplying also general non-mathematical information such as results of tests to establish whether the mathematics really fits. (Incidentally there is now a sixth edition (1927) in English translated by Löwenstein.)

Steam turbines also involve a great deal of dynamics of fluids with which the book is not concerned, though one would not know that from the title. (Presumably "dynamik" in German has a somewhat different connotation from "dynamics" in English.) Damping and hysteresis receive little mention; actually internal damping of blade materials is probably as important to the designer as other factors in the calculations. Hysteresis can also lead to whirl of shafts. There is a great deal more known about the behaviour of a shaft in a bearing, e.g. oil whip, than the authors' treatment or even their references suggest.

A danger of such a book is that it tends to lead a young man to think that things behave according to the mathematical assumptions or conversely that what is not mathematically tractable cannot be tackled. An example is the treatment of lacing wires. It is known that these generally come loose if an attempt is made to fasten them, so many makers leave them loose deliberately. They are still useful as damping wires, though they do not then function as the authors describe on page 127. *B. W.*

Principles of Nuclear Reactor Engineering *by Samuel Glasstone. 6 in. by 9·25 in., 861 pp. London: Macmillan and Co. Price 60s.*

Up till now, nuclear reactors have on the whole been designed mainly by physicists with the assistance of engineers, but the situation is rapidly approaching—if indeed it has not already arrived—when the engineer will have to do the job himself. The theory of designing a reactor is by now well codified and is not particularly difficult, although many questions of fundamental importance to the physicist remain unanswered—some may say unanswerable. These, however fascinating they may be, need not deter the engineer, who is well used to ignoring what he considers inessentials and making something which, for all his ignorance, works.

The latest volume from Dr Glasstone's prolific pen will do nothing but enhance his already considerable reputation in this country, although, like many American writers, he is inclined to do something less than justice to British achievements. Here, in a well-ordered assembly, are all the data and basic theories which engineers will need for the necessary background to more advanced studies. As little space as possible in what is already a very long book is given to questions of atomic structure, the author tacitly assuming—and rightly—that this is readily accessible elsewhere, and so the reader is very quickly introduced to the theory of the reactor itself, both in the steady and disturbed states. Following this extensive treatment are chapters on instrumentation and control, fuels and reactor materials, protection and shielding, thermal aspects of power generation and a valuable discussion on current thought about complete power installations. The volume concludes with a description of some actual and projected plants. These are nearly all American, although GLEEP and BEPO are mentioned, as are some of the European reactors.

The history of the book is interesting since it was written for the AEC on the recommendation of the American Society for Engineering Education which wanted an unclassified textbook in order to advance nuclear engineering education in the United States. In this, Dr Glasstone and his highly professional team of writers have admirably succeeded and the work could well provide a basis for a post-graduate course in this country. *W. D.*

SIMA Directory & Handbook 1956 *London: Scientific Instrument Manufacturer's Association, 20 Queen Anne St, W1. Price 32s. 6d.*

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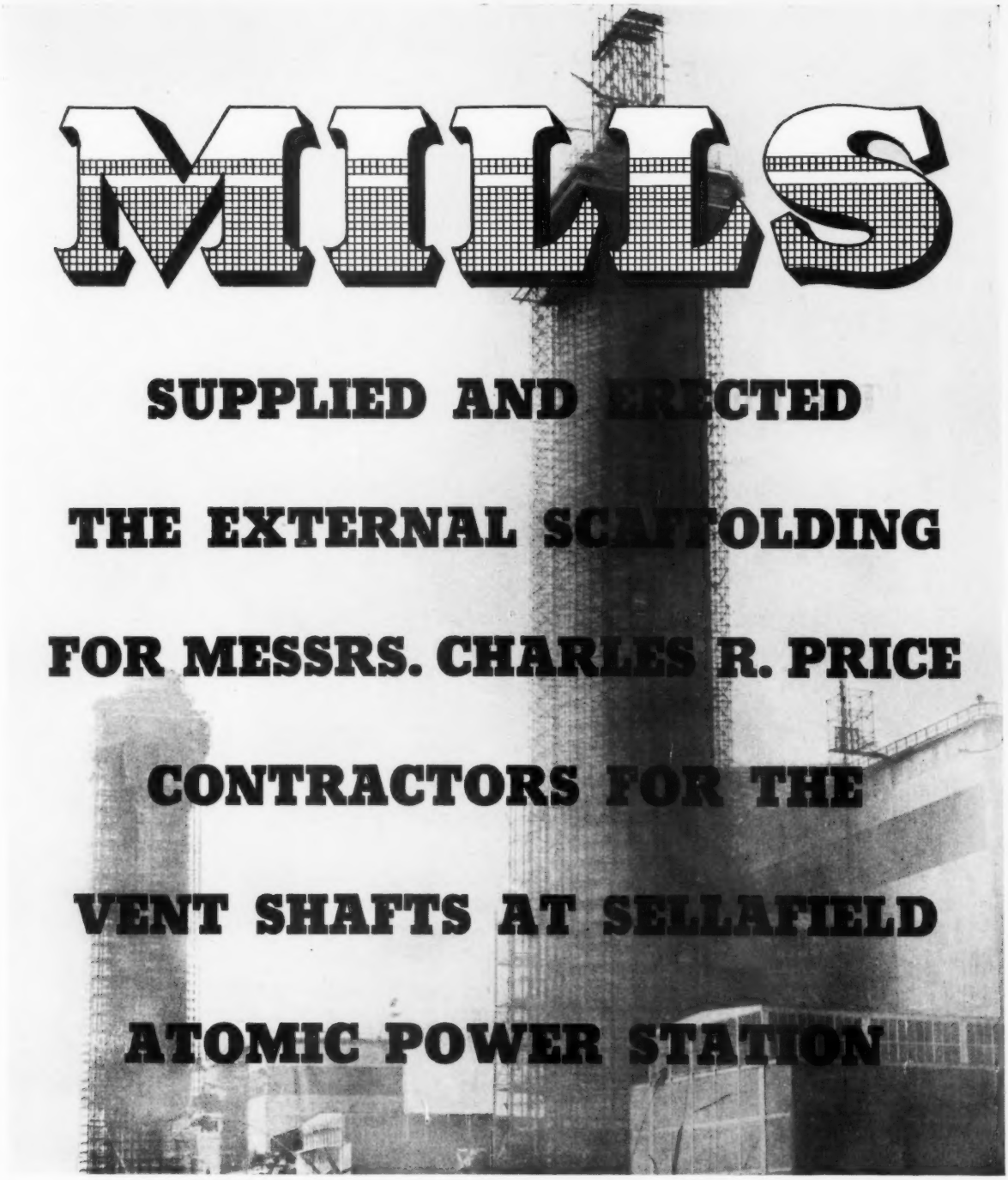

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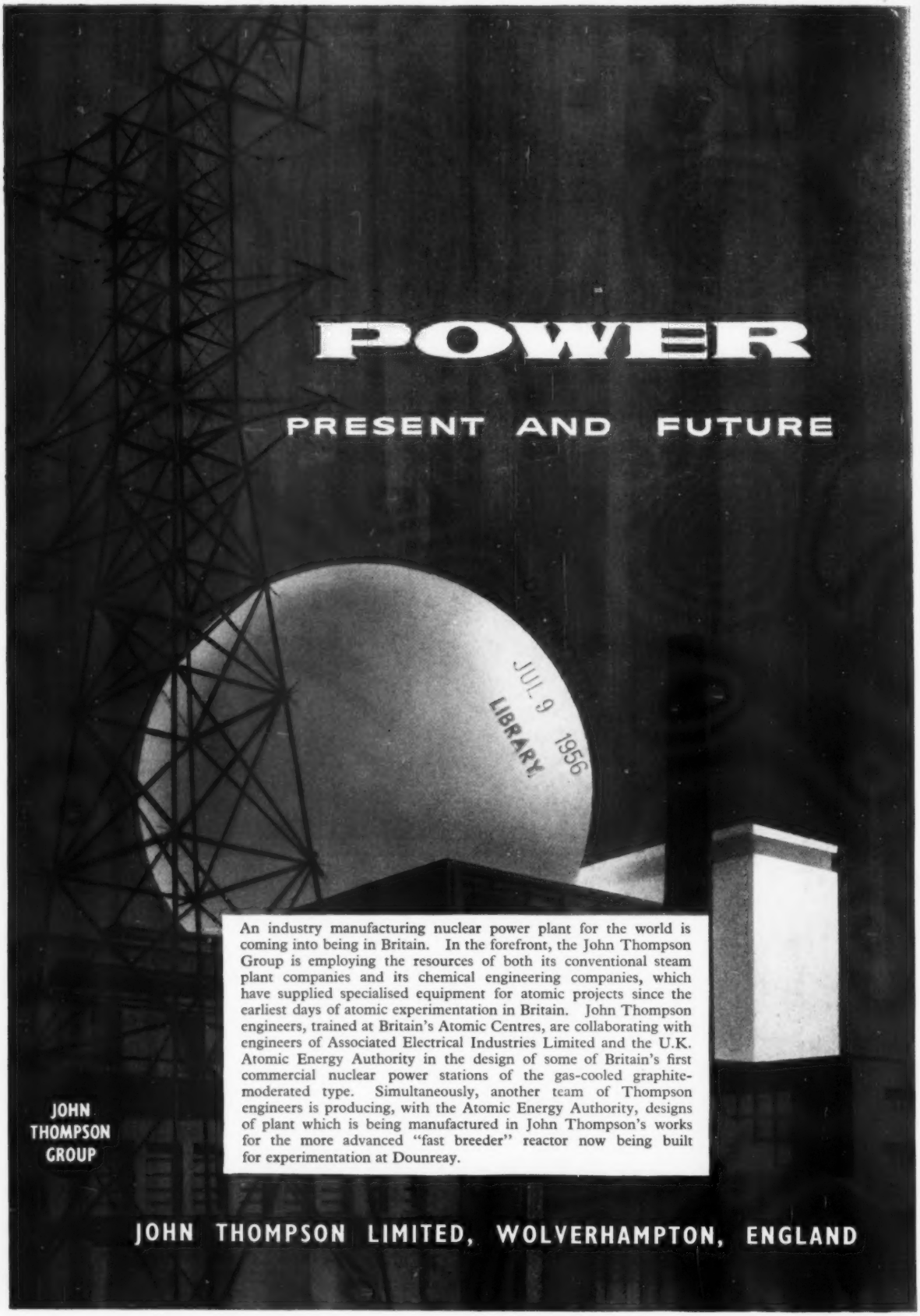
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